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Performance Evaluation of the Braintree Electric Light Department Dry Cooling Tower

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Denver, CO

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PERFORMANCE EVALUATION OF THE BRAINTREE ELECTRIC LIGHT DEPARTMENT DRY COOLING TOWER

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16. ABSTRACT The report gives results of a 5-year evaluation of the performance of a dry cooling tower for the 20-MW steam-electric generation portion of an 85-MW combined-cycle power plant. Objectives of the study were to: demonstrate dry cooling tower technology at a Massachusetts seacoast site, document and optimize heat rejection performance, evaluate the effect of dry cooling tower operation on the environment, and define the effect of environmental conditions on dry cooling tower performance. Since plant startup in 1977, the unit has been on-line for only about 2100 hours due to several equipment failures associated with the gas turbine which caused 17 months of forced outage. Another major reason for low utilization was the escalating cost of fuel oil. Originally conceived as an intermediate load unit, high fuel costs shifted it to peaking service. This decreased operation reduced the scope of the originally planned demonstration. During 1979 and 1980, the performance of the dry cooling tower was close to design. The combined-cycle heat rate has always exceeded its design value; it was about 10% higher in 1980. Data collected were inadequate to demonstrate the freezing and corrosion resistance of the tower's finned tubes or the noise generated by the dry cooling tower apart from the entire combined-cycle unit.

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Cooling Towers	Stationary Sources	13A, 07A, 13I
Electric Power Plants	Heat Rejection	10B
Performance Freezing		14G 07D
Evaluation Noise		20A
Corrosion		11M

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ABSTRACT

The performance of a dry cooling tower for the 20 MW steam-electric generation portion of a 85 MW combined-cycle power plant was evaluated in a 5-year project. Under a grant to the Braintree Electric Light Department, the objectives of the demonstration were to demonstrate dry cooling tower technology at a Massachusetts seacoast site, document and optimize heat rejection performance, evaluate the effect of dry cooling tower operation on the environment, and define the effect of environmental conditions on dry cooling tower performance.

Since startup of the plant in 1977, the unit has been on-line for only about 2100 hours due to several equipment failures associated with the gas turbine which caused 17 months of forced outages. Another reason for low utilization has been fuel escalation, which has resulted in current prices approximately six times as high as anticipated. This decreased operation reduced the scope of the originally planned demonstration.

Monitoring equipment detects deviations in steam-turbine operation, dry cooling tower heat rejection and combined-cycle heat rate. A data logger receives information on steam turbine parameters, fan operation, power generation, air temperatures upstream and downstream of the fintube bundles, condensate temperatures and fuel flow.

Data for approximately 350 hours of operation in 1979 and 1980 have been analyzed. The performance of the dry cooling tower is reasonably close to design when condensate temperatures are analyzed. However, at ambient temperatures above approximately 60° F a deterioration in performance is noticeable. It is possible that seasonal adjustments to the pitch angle of the fan blades is warranted in overcoming this problem.

The combined-cycle heat rate has always exceeded the design value (about 10 percent higher in 1980), even though it has decreased since initial operation. The problem is thought to be with the gas turbine combustor. Adjustment to compressor air flow and combustion temperature may allow reduction of the heat rate to a lower value.

Recirculation of hot exhaust air from the dry cooling tower to the fan inlet happens only to the bank of cells closest to the combined-cycle plant building. The causes for this recirculation are unknown but investigation of potential flow paths are planned.

Available data are inadequate to demonstrate the freezing and corrosion resistance of the fintubes or to address the noise generated by the dry cooling tower apart from the entire combined-cycle unit. There is no data that would indicate passage of the dry tower plume in the downwind environment.

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1. INTRODUCTION

The purpose of this report is to present the results of performance evaluation of the dry cooling tower serving Braintree Electric Light Department's combined-cycle power plant. This project was initiated with an EPA-sponsored demonstration grant in December, 1975. Several areas of investigation were planned, the most important being optimization of plant performance. The plant became commercial in April, 1977. Performance monitoring equipment was leased and installed between September, 1976 and June, 1978. During 1978 two separate failures of gas turbine equipment occurred. Another gas turbine equipment failure occurred early in 1980. The total forced outage time to date is approximately 17 months. Because of increases in the price of gas turbine fuels, the plant is currently used only for peaking service, rather than for intermediate load service as anticipated. At the time of preparation of this final report only about two thousand hours of operation have been accumulated. Thus the program envisioned at the start of this project has been greatly curtailed even though the original grant period of four years was extended for one year.

The objectives of the program were to demonstrate dry cooling tower technology and to document and optimize heat rejection performance. The effect of environmental conditions on performance and the effect of operation on the environment were to be defined. Provisions were made in plant design to utilize residual oil for fuel resulting in a performance penalty. However, only distillate oil has ever been used.

When the unit is needed by the NEPOOL system, typical operation occurs during the week from mid-morning to early evening at nominal full-load conditions. Actual operation has been spread throughout the year. Data from 16 days in 1979 (approximately one-third of all operation) and 28 days in 1980 (approximately one-half of all operation) are available and have been analyzed. These data form the basis of this report. Three-fourths of the data were obtained during summer and fall when high ambient temperatures cause the most difficult service for the dry cooling tower. Consequently very little information has been gained towards potential freezing problems.

This report is divided into the following sections:

(1) The Background section describes the initial concept behind this project, equipment failures which have resulted in substantial downtime and current operating economics responsible for dispatch of Potter No. 2.

(2) The Monitoring Equipment section describes the selection, installation and operation of air quality monitors, meteorological sensors, steam turbine parameter relay to the data logger, power transducers for fan operation and power generation relay to the data logger, thermocouple sensing of air temperature upstream and downstream of the fintube bundles, thermocouple sensing of condensate temperature, and fuel flow meters for combustion analysis. Pressure transmitters intended to monitor air flow did not give sufficiently accurate measurements and were never permanently installed. A laboratory was equipped to do fuel and corrosion analyses but was rarely utilized. A number of meteorological and air quality instruments have failed periodically and the planned accumulation of data on magnetic tape has been unsatisfactory.

(3) The Data Collection/Analysis section describes the comprehensive performance data obtained by operating personnel and reduced from paper tape. The logic employed in preparing a computer program to analyze the data is also discussed.

(4) The Results section describes plant operation in general and compares actual dry cooling tower performance to expected performance and actual heat rates to design heat rates. Local heat transfer along one cooling tower cell and the occasional occurrence of recirculation of exhaust air to fan inlet were also investigated.

(5) The Conclusions section describes the performance of the dry cooling tower and the entire combined-cycle plant.

The Appendices provide further information as follows:

(1) The Computer Program appendix lists the Fortran program and provides sample input/output.

(2) The Noise appendix describes design considerations for the dry cooling tower and the entire combined-cycle plant and discusses conformance with specifications on the basis of survey data.

(3) The Air Quality appendix comments on the severity of parameters which may affect corrosion over the time period from design of the plant to the present.

(4) The Corrosion appendix qualitatively assesses visible rust.

2. CONCLUSIONS

BELD's combined-cycle unit has not operated nearly as frequently as planned due to the substantial increase in fuel oil cost subsequent to its design and construction. There have also been substantial forced outages due to major failures of gas turbine equipment. However, with rebuilding and increased operating experience the performance of the unit has improved.

While it has not been possible to optimize the performance of the dry cooling tower, monitoring equipment is available to detect deviations in steam-turbine operation, dry cooling tower heat rejection and combined-cycle heat rate. Ambient temperature is the most important environmental condition affecting dry tower performance and unit output. Available data are inadequate to demonstrate the freezing and corrosion resistance of the fintubes or to address the noise generated by the dry cooling tower apart from the entire combined-cycle unit. There are no data that would indicate passage of the dry tower plume in the downwind environment.

Data from approximately 350 hours of operation in 1979 and 1980 have been analyzed. The performance of the dry cooling tower is reasonably close to design when condensate temperatures are analyzed. It appears that pressure measurements are not as accurate as temperatures in this regard. However, at ambient temperatures above approximately 60°F*, a deterioration in performance is noticeable. It is possible that seasonal adjustments to the pitch angle of the fan blades (to increase air flow in the summer) is warranted to overcome this problem.

The combined-cycle heat rate has always exceeded the design value, even though it has decreased since initial operation. The problem is thought to be with the gas turbine combustor since steam cycle parameters and gas turbine generator output are reasonably close to design values. Adjustments to compressor air flow and combustion temperature may allow reduction of the heat rate to a lower value.

Recirculation of hot exhaust air from the dry cooling tower to the fan inlet happens only to the bank of cells closest to the combined-cycle plant building. The causes for this recirculation are unknown but seem to be related to the diminished heat transfer of the lower portion of south-side fintubes on Cell 2A-4. Otherwise, heat transfer seems to be uniform across individual cells and the entire dry cooling tower.

* English system units rather than metric have been used in this report because the English system remains the standard in the utility industry. A conversion table is included as Appendix E.

3. BACKGROUND

The Braintree, Massachusetts Electric Light Department (BELD) operates an 85 MW combined-cycle (gas turbine-steam turbine) electric generating unit known as Norton P. Potter Station, Unit No. 2. The exhaust heat from the 65 MW gas turbine is utilized in an unfired heat recovery boiler to produce steam for a 20 MW steam turbine. Because of the utilization of gas turbine waste heat, the generating unit has a relatively high thermal efficiency. The design net heat rate, i.e. the amount of fuel energy consumed to produce a kilowatt-hour (kWh) of electricity, for the unit is 9,080 Btu/kWh (38 percent thermal efficiency), which is considerably better than most generating alternatives. The site and the major combined-cycle equipment locations are illustrated in Figures 1 and 2, respectively.

During the course of the preliminary design and environmental investigations for Potter No. 2, it became evident that it would be costly and time-consuming to attempt to secure permits for an open-cycle cooling system.[1] The use of water from the Weymouth Fore River Estuary would require permits from the various federal, state, and local agencies concerned with environmental quality. A study of alternative methods for cooling the plant showed that an air-cooled condenser would result in an estimated power cost 2 percent higher than the cost of power using an open-cycle system. In addition, due to the relatively high cost of clean water suitable for use in evaporative cooling towers ($0.70 per 1000 gal.) the power cost using the air-cooled condenser was estimated to be no higher than using evaporative towers.

The two parameters of greatest concern in evaluating dry tower performance are the turbine backpressure and the initial temperature difference (I.T.D.) between condensing steam and ambient air.[2] Turbine heat rate decreases with decreasing backpressure and the amount of fintube surface required for a specified duty varies inversely with I. T. D. The GEA dry tower for Braintree was selected on the basis of 3.5 in. Hg backpressure, and a design I. T.D. of 62 F. These particular design values were chosen as a result of engineering investigations which showed that the benefits of unit operating economy offset the initial capital cost penalty for this size tower. The other design data for Potter No. 2 are given in Figure 3.

INITIAL CONCEPT

As originally conceived, the main objectives of this study were the documentation of performance and optimization of operation of the heat rejection system for the combined-cycle power plant. Other objectives included documentation of the corrosion and freezing characteristics of the fintube bundles, demonstration of the attenuation of dry cooling tower noise to levels within the regulatory limit, and identification of possible meteorological impact of the heat rejection system on the local environment. The plan was to gather operating data over 3 calendar years and about 15,000 hours of operation.

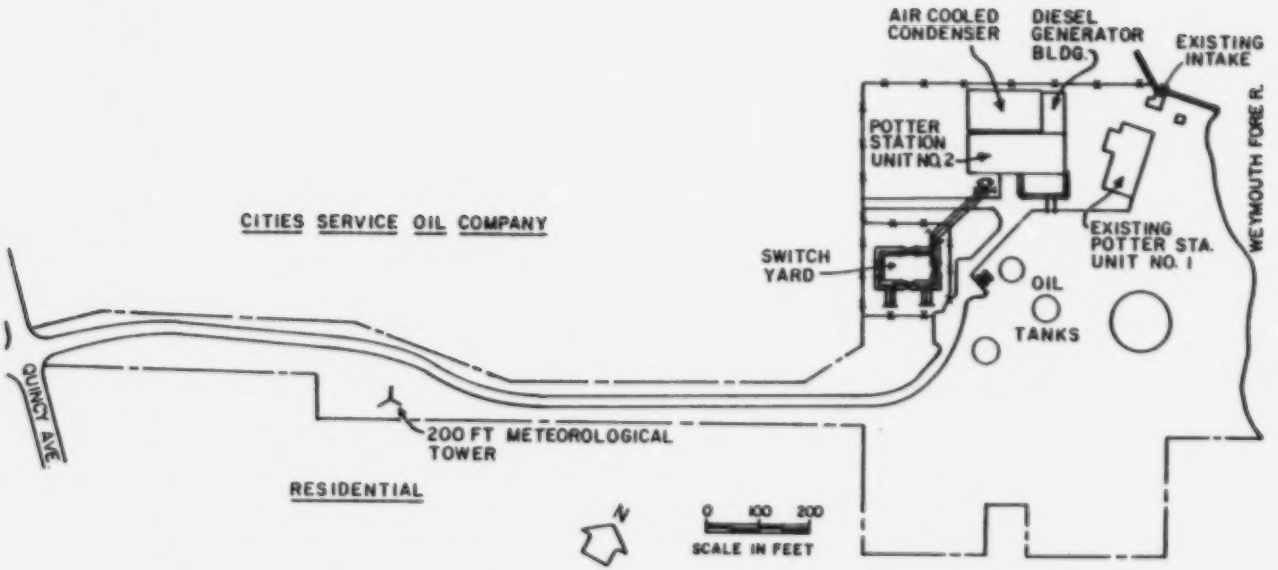
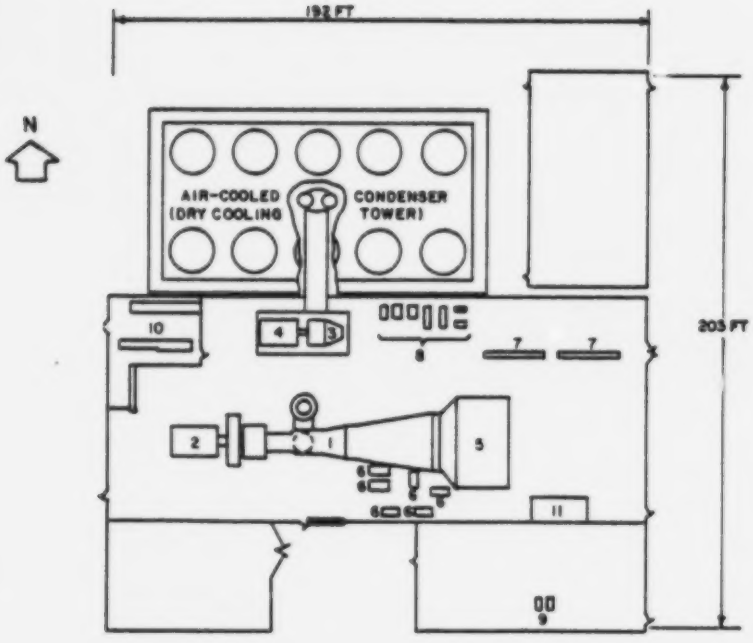


FIGURE 1. SITE PLAN FOR POTTER STATION; EAST BRAINTREE, MASS.



1 – GAS TURBINE
2 – GAS TURBINE GENERATOR
3 – STEAM TURBINE
4 – STEAM TURBINE GENERATOR
5 – HEAT RECOVERY BOILER
6 – BOILER CIRCULATING PUMPS
7 – 480 VOLT MOTOR CONTROL CENTERS
8 – FEEDWATER AND CONDENSATE PUMPS
9 – FUEL FORWARDING PUMPS
10 – CONTROL ROOM
11 – LABORATORY

FIGURE 2. PLAN VIEW OF COMBINED CYCLE UNIT

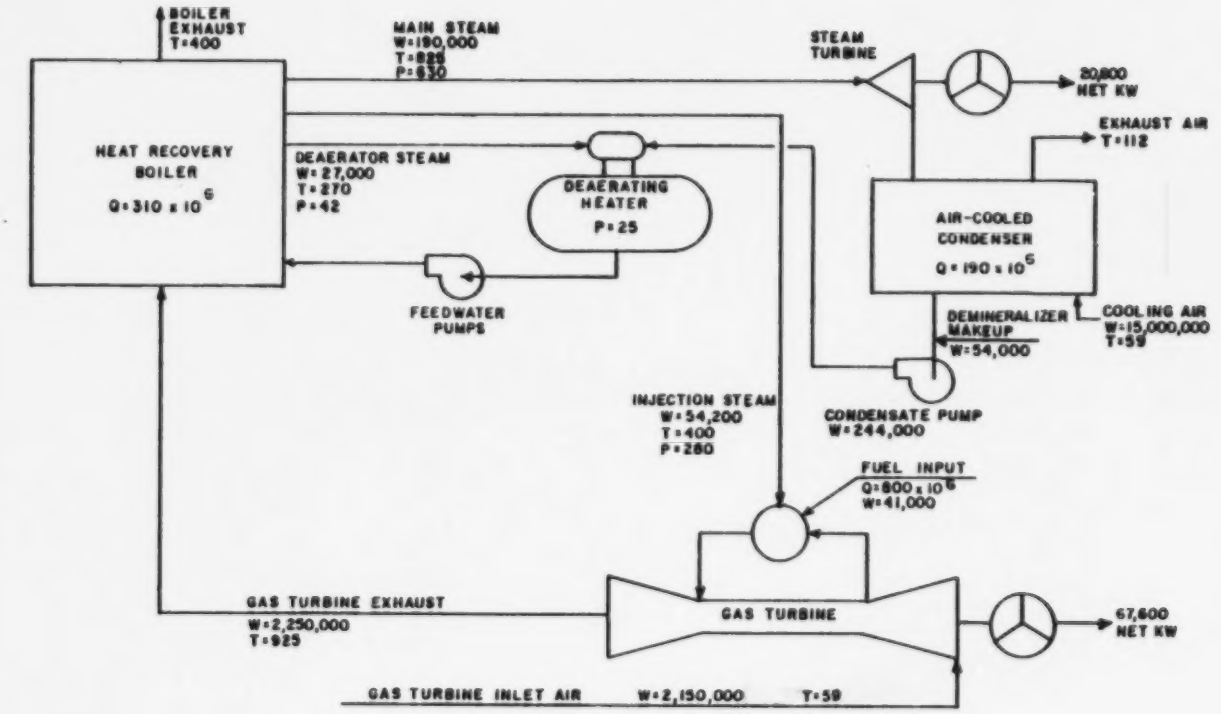


FIGURE 3. COMBINED-CYCLE FLOW DIAGRAM

Expected heat transfer characteristics can be related to the status of each of the 10 fans with the GEA - supplied operating diagram for a given steam flow and ambient temperature (see Figure 4). The actual heat transferred from the steam to the atmosphere is a function of steam flow and backpressure and is reflected by the temperature change of the cooling air. The subcooling of the condensate is expected to be negligible, therefore, latent heat represents essentially all the heat transferred. Instrumentation monitors all of these parameters. Processing of the data allows comparison of the expected and actual turbine backpressure. A further aspect of the study is documentation of localized heat transfer in a particular cell (forced-draft fan and enclosure comprised of fintube bundles aligned in an A-frame structure) by measuring air flow and temperature difference. The purpose of this effort is to document the effective portion of the fintube bundles.

There are 130 inputs to the data logger which are interrogated on a once-every-five-minutes basis. There are 2 air quality sensors, 17 meteorological sensors, 2 fuel flow transmitters, 4 steam parameter sensors, 68 thermocouples in air, 3 thermocouples in condensate lines, 19 differential pressure sensors and 15 power transducers.

Ambient air drawn through the dry cooling tower is monitored for SO_2 and NO_x concentrations for purposes of comparison to air quality standards and for possible correlation with corrosion of the fintube surface. The alarm monitoring function of the data logger may be used to single out high pollutant levels. In addition, high-volume particulate samples are run on a regular basis and manually added to the averaged data tape. Dirty filter papers are analyzed for trace metals and chloride content.

The primary purpose of the 200-ft meterorological tower, located approximately 1200 feet southwest of the dry cooling tower on a hill some 50 feet above grade at the Unit 2 location, is to record the effect of the dry tower plume on the environment. Temperature sensors at seven levels are used in this analysis. Wind directions appropriate for directing the plume at the meteorological tower may be alarmed at the data logger. Other parameters useful in determining the stability of the lower atmosphere, e.g., sigma azimuth angle, temperature profile, wind speed and solar insolation, are recorded by the data logger. Additional meteorological parameters of general interest, including pressure, precipitation and relative humidty, are also recorded.

Net fuel oil consumption (determined by difference between the flow to and from the gas turbine combustion chamber) in a given time period is used to check the gross power output of the gas turbine. This information is primarily useful in evaluating the optimum net power output of Unit 2 for a given fuel consumption.

The steam parameters monitored included flow to the turbine, inlet conditions (temperature and pressure), and turbine backpressure. This information is used to determine dry cooling tower duty and gross power output of the steam turbine. The alarm monitoring capabilities of the data logger may be used to help maintain turbine backpressure within a specified range.

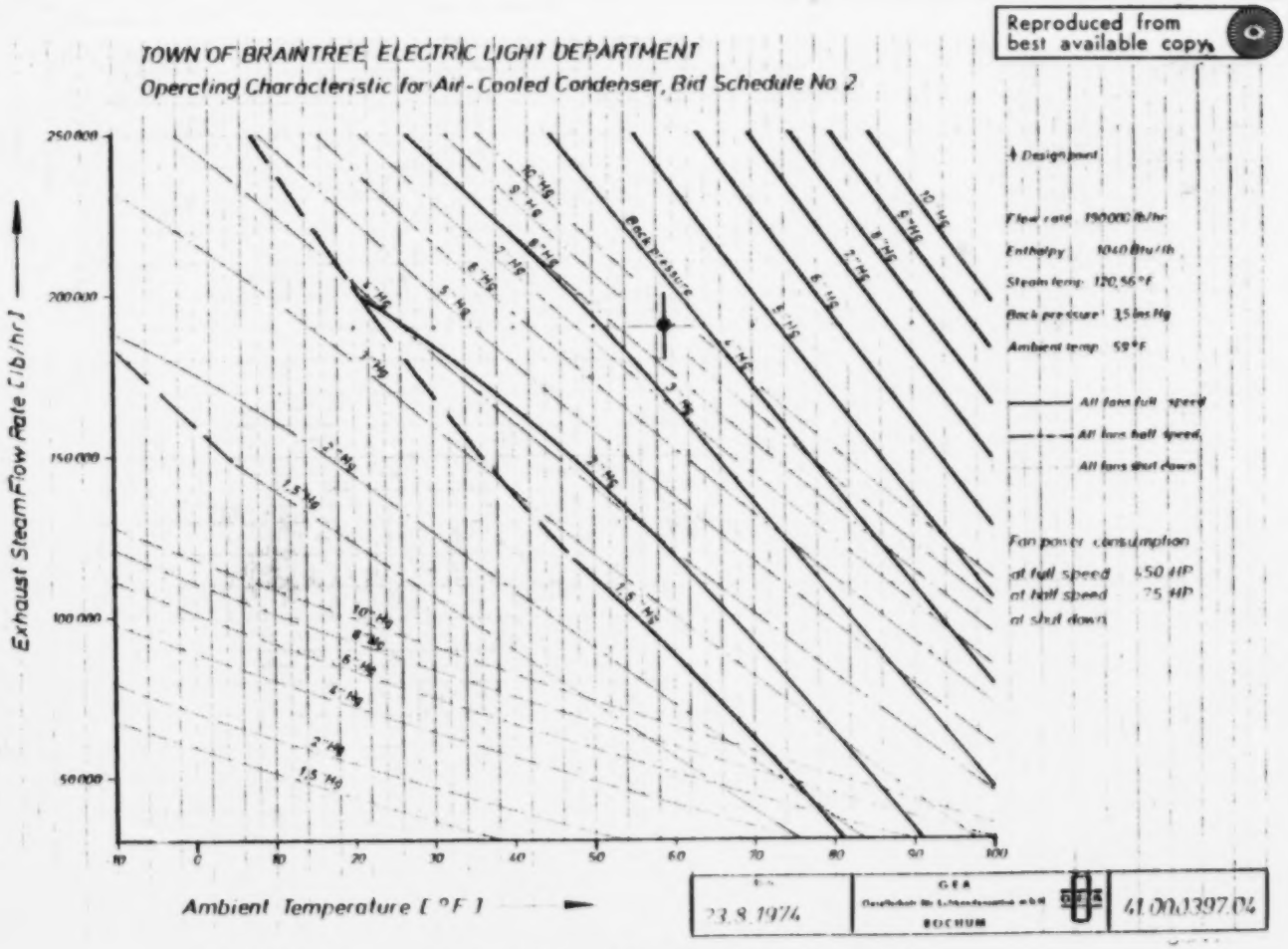


FIGURE 4 DRY TOWER OPERATING DIAGRAM

The ambient air thermocouples on nine of the dry tower cells monitor inlet air temperature and exhaust air temperature (on each side of the A-frame). This information (along with air flow data as a function of fan characteristics) is used to quantify relative heat flux and to investigate possible recirculation. One particular cell (designated 2A-4, which is the first condensing cell to be operated as duty increases after the initial dephlegmating cell is loaded) is equipped to study localized heat transfer with a rosette pattern of five thermocouples below the fan shroud, and 3 x 3 pattern of thermocouples on the plenum and exit sides of each half of the A-frame (see Figures 5 and 6).

Condensate temperatures from each bank of the dry tower as well as from the center fintube bundle (south side) of cell 2 A-4 monitor sub-cooling by means of pipe thermocouples. The alarm monitor may be set to indicate temperatures outside of the expected range. Maldistribution of steam within the fintube bundles, or sub-cooling of the condensate, may also be manually investigated with a remote-sensing thermometer.

Differential presssure sensors are used for two different purposes. Nine of the cells are monitored for static pressure change as an indication of the buildup of air contaminants between the fin surfaces. The effect of this increased pressure drop is to decrease air flow and impress a higher temperature difference across the fintube (between plenum and exhaust air). From these data criteria may be developed on the required frequency of cleaning of fintube bundles. Localized flows on cell 2A-4 are documented with velocity pressure sensors in rosette patterns (five sensors) on each side of the A-frame. This information (in addition to the termperature difference measurements referred to above) is used to compute localized heat transfer.

Ten of the signal converters monitor power input to the dry cooling tower fans. These two-speed fans are expected to show approximately a factor of eight difference in power consumption with speed. This information relates to expected turbine backpressure with GEA's operating diagram (Figure 4) and steam flow and ambient temperature. These parameters also correlate with the static pressure measurements. Gross power output from the gas and steam turbines is monitored and compared with expected values. Unit 2's auxiliary power consumption (comprised in part by the cooling tower fans) is monitored directly. Net power to the busbar also is monitored and equals gross output less auxiliary consumption. The primary purpose of this comparison is to determine if less auxiliary power usage (in the form of fan power) would increase net power output more than the higher steam turbine backpressure (which would decrease the gross output of that generator) would decrease it.

Other than the sensors described above, laboratory furniture, equipment and supplies are involved in the air quality and fintube corrosion phases of the performance studied. Noise measurements are taken as a separate task from the analysis of the data logger's tape records. An on-site trailer functions as office for the research technician and suitable habitat for the data logger and air quality monitors.

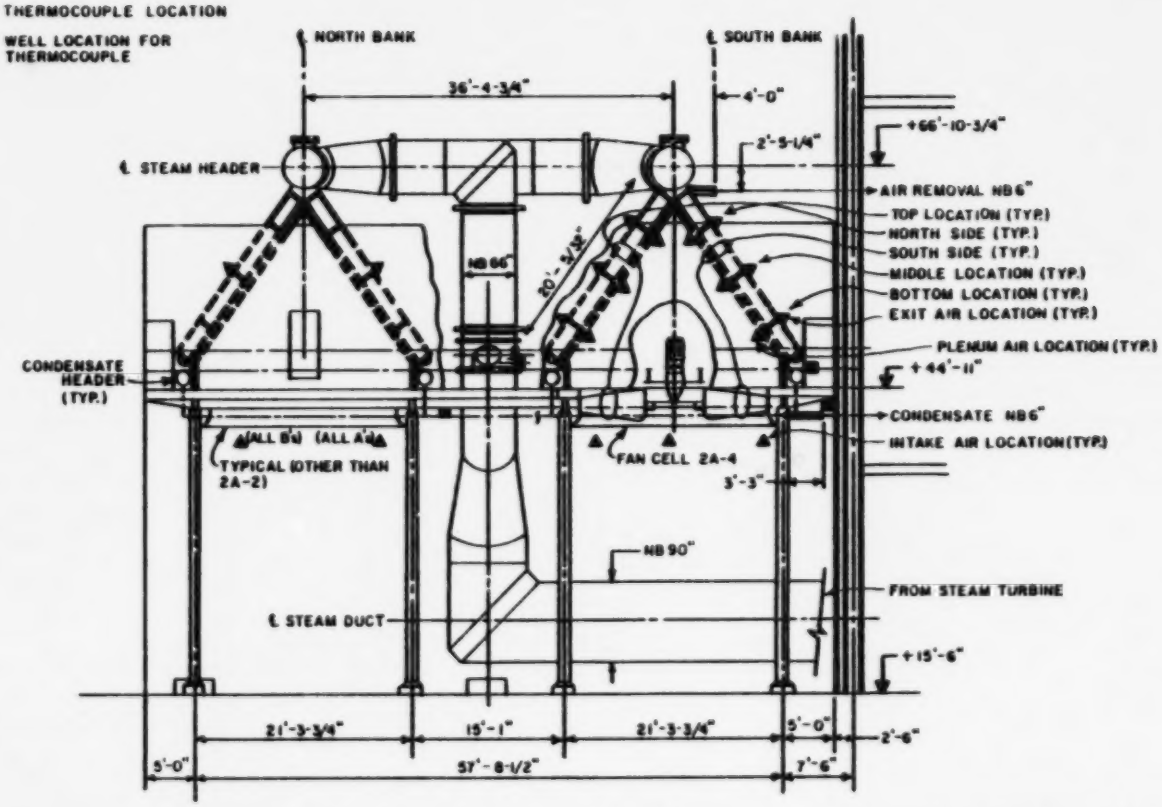


FIGURE 5. AIR-COOLED CONDENSER THERMOCOUPLE ELEVATION LOOKING EAST

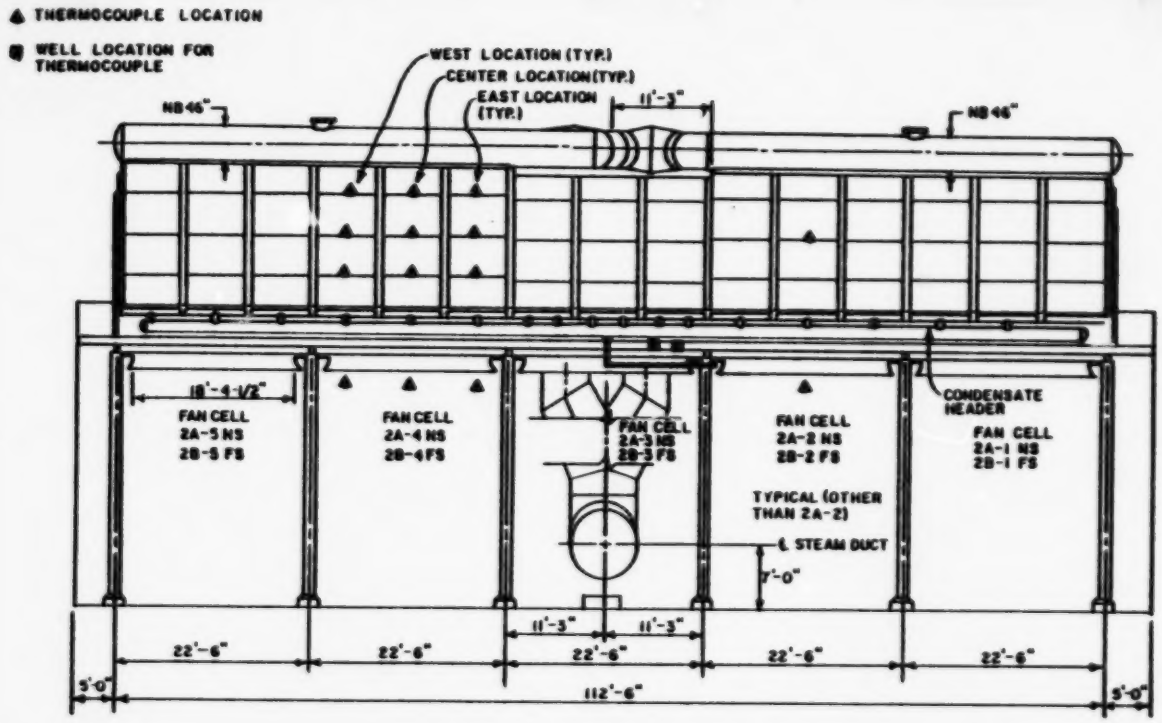


FIGURE 6. AIR-COOLED CONDENSER THERMOCOUPLE ELEVATION LOOKING NORTH

PLANT HISTORY

In late 1972, BELD decided a combined-cycle power plant should be built at the Norton P. Potter Generating Station site as part of their overall power supply program. A chronology of plant construction is presented in Table 1. The plant is dispatched by the New England Power Pool; NEPOOL is the popular designation for this organization consisting of member electric utility companies in the northeastern United States. NEPOOL members must own (directly or indirectly) adequate generating facilities to fulfill their own peak capacity demands, including a specified level of reserve capacity; these facilities are then operated like one large utility system to supply energy from the facilities to the NEPOOL system at the lowest cost.

TABLE 1. CHRONOLOGY OF PLANT CONSTRUCTION

Date	Event
Late 1972	Preliminary design, financial planning, and environmental studies began.
Late 1973	Major equipment contracts awarded
Late 1974	Foundations installed
Early 1975	Steel erected
Late 1975	Building completed
Late 1975	Equipment and mechanical and electrical installation began
Early 1975	Startup performed

Braintree's Potter Station Unit No. 2 was designed specifically to take advantage of the benefits of membership in NEPOOL. Based upon the costs of capital and fuel in 1973, when the decision was made to construct the plant, it was estimated that Potter Station Unit 2 would be operated in NEPOOL for approximately 5000 hours per year. By the time the unit was placed in service in 1977, fuel costs had risen to a level approximately 3 times the 1973 level, and by 1980 had risen further to nearly 7 times the 1973 prices (see Table 2). This increase in fuel cost has shifted the status of Potter No. 2 in the NEPOOL group of generating facilities from that of an intermediate load unit, normally operating between 3000 and 5000 hours per year, to a peaking generation unit, operating only 1000 to 1500 hours per year. This situation does not negate the value of the unit to Braintree, nor does it make the unit valueless to NEPOOL; it simply changes the way in which NEPOOL utilizes Potter No. 2 to minimize the cost of generating electric energy for all of the NEPOOL numbers.

TABLE 2. COMPARISON OF FUEL COSTS

Period	Original Estimates 1973	Actual Conditions 1977[a]	Actual Conditions 1978	Actual Conditions 1979	Actual Conditions 1980[b]
Annual Generation, MWh	430,000	43,300	26,500	40,200	46,600
Fuel Costs, $/10^6 Btu	0.90	2.56	2.63	2.75	5.61
Heat rate, Btu/kWh	9,080	10,500	10,400	10,300	9,900
Comparable Fuel Costs, mills/kWh	8.2	26.9	27.4	28.3	55.5

(a) Partial year 4/1-12/31 (b) Partial year 1/1-10/31

TABLE 3. OPERATING HISTORY

Period	4/1/77-2/22/78	7/1/78-8/14/78	4/1/79-1/29/80	8/1/80-10/31/80
Operating time (total fired time) tf, hr	824	101	806	359
Outage time (unit not available) to, hr	959	8	150	240
Total time in period, tp hr	7,872	1,080	7,296	2,208
Energy produced, ep, MWh	62,100	7,300	59,000	27,800
Availability factor[a], A.F., percent	87.8	99.3	97.9	89.1
Utilization factor[b], U.F., percent	10.5	9.4	11.0	16.3
Net running capacity factor[c], NRCF, percent	9.3	7.9	9.5	14.8

(a) $A.F. = \frac{tp-to}{tp} \times 100$ (b) $U.F. = \frac{tf}{tp} \times 100$ (c) $NRCF = \frac{ep}{85 \times tp} \times 100$

The operating history of the unit is presented in Table 3. Although avilability has been good during operating periods, forced outages have been persistent. Of 43 months covered in Table 3, forced outages have amounted to 17 months. The average avilability of the unit exceeds 90 percent. Only in late 1980 has utilization significantly exceeded 10 percent, although operation is normally close to capacity.

During 1977, boiler vibration and air leakage problems were diagnosed and remedied. The flow of gas through the turning vane section of the boiler caused significant vibration of boiler walls, turning vanes and supports. This vibration and the resulting noise was objectionable to nearby residents and caused cracking of welds and tearing of sheet metal components in the boiler turning vane section. Significant modifications were made during May through July, 1977 to the turning vane section including use of alloy materials in place of carbon steel, continuous welds in place of intermittent welds, heavier structural members, and use of pinned and sliding attchments in place of rigid attachments of internal turning vanes to the boiler structure.

The large (6-ft diameter) flanges where the gas turbine u-duct connects to both the gas turbine casing and the combustion chamber also developed significant leaks, allowing 500° F air to escape into the plant building. Different gasket materials and assembly procedures were investigated and tried before the problem was solved.

On February 23, 1978, a hot gas path inspection revealed major deterioration of gas turbine blades, u-duct support trunions, and combustion chamber internals. The unit was taken out of service, completely overhauled, and returned to service on July 1, 1978 (total outage time = 128 days).

On August 14, 1978 during an attempt to start the unit, an explosion occurred inside the gas turbine and caused extensive damage to the combustion chamber, u-duct, and turbine blades. The gas turbine was completely rebuilt and modifications were made to the fuel supply controls and safety system in an effort to eliminate the apparent cause of the explosion. The unit was returned to service on April 1, 1979 (total outage time = 229 days).

On January 29, 1980 the unit was running at full load when several operating parameters were noticed to shift significantly over a period of about 20 minutes. The plant operators took action to shut the unit down, but while the load was being reduced in preparation for shutdown the outer wall of the combustion chamber ruptured releasing approximately 1800° F gas into the plant area and discharging pieces of metal and insulating material. Later investigation indicated that some of the combustion chamber internal parts had either deformed or shifted in such a way as to allow the hot gas to fill a space normally occupied by 500° F compressed air. This caused the metal wall of the combustion chamber to weaken until it ruptured. The combustion chamber and the u-duct were completely rebuilt, and the power turbine blades were overhauled. The unit was placed back into service on August 1, 1980 (total outage time = 184 days).

4. MONITORING EQUIPMENT

In order to accomplish the planned monitoring described in Section 3, a specification was prepared for instrumentation to be leased by BELD. The chronology of specification, contract award, installation and operation is described in Table 4. Particular performance specifications for the thermocouples, pressure transducers, meteorological system, and data acquistion system are discussed below. Laboratory equipment and signal converters are discussed later in this section. The air quality analyzers and auxiliary equipment are described in Appendix C.

Type T thermocouples with a range of -75° F to 200° F and an accuracy of $+0.75^{\circ}$ F were specified for monitoring ambient and exhaust air temperatures relative to the cooling coils (see Figures 5 and 6). Solid state differential pressure transducers with a range of 0-5 in. H_2O and an accuracy of 0.5% were specified for monitoring static and velocity pressures across the cooling coils. The 200 ft meteorological tower has wind instruments at three levels. The anemometers were specified with a range of 0.5 to 100 mph and an accuracy of $\pm$0.2 mph. The wind vanes were specified with an overlapping range of $0\text{-}540^{\circ}$ and an accuracy of $\pm 3^{\circ}$. Temperature sensors at five levels and differential temperatures from 30 to 200 feet are also mounted on the tower. Industry standard sensors were found to be at least as accurate, but with less range, than the thermocouples installed on the dry cooling tower. Standard instruments were also specified for barometric pressure, relative humidity, solar radiation, precipitation, and sigma azimuth angle. All the meteorological instrument outputs are electronic with signal conditioning to provide similar voltage levels.

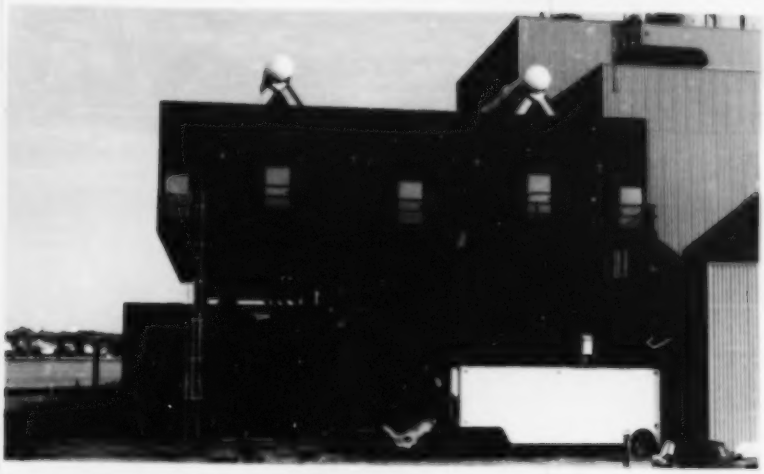
The heart of the monitoring system is the data logger installed in an instrument trailer adjacent to the dry cooling tower (see Figure 7). The data logger was specified to have expanded channel capacity, output to both magnetic tape and a printer, and display on an integrating digital voltmeter (see Figure 8). Multiplexing, scanning, linearization, totalizing, and alarm monitoring functions were required. Input modes to accomodate thermocouples, resistance, voltage and current analogs, and digital input were required. Rack monitoring was specified.

A contract was awarded to Radian Corporation in November, 1976 for the air quality monitors, instrument trailer, dry cooling tower operation sensors, data acquistion systems, and laboratory equipment. A contract was awarded to Meteorology Research, Inc. for the meteorological system.

TABLE 4. CHRONOLOGY OF PERFORMANCE MONITORING

Date	Event
12/75	Demonstration grant approved
7/76	Parameters and equipment identified
9/76	Equipment lease and laboratory furniture specifications prepared
11/76	Contracts awarded
3/77	Installation specification prepared
6/77	Installation by BELD personnel approved
10/77	Contractor supplied equipment delivered
3/78-6/78	Forced outage
6/78	BELD Installation of monitoring equipment completed
9/78-3/79	Forced outage
5/79-8/79	Data collected
1/80	Data collected
2/80-7/80	Forced outage
8/80-10/80	Data collected

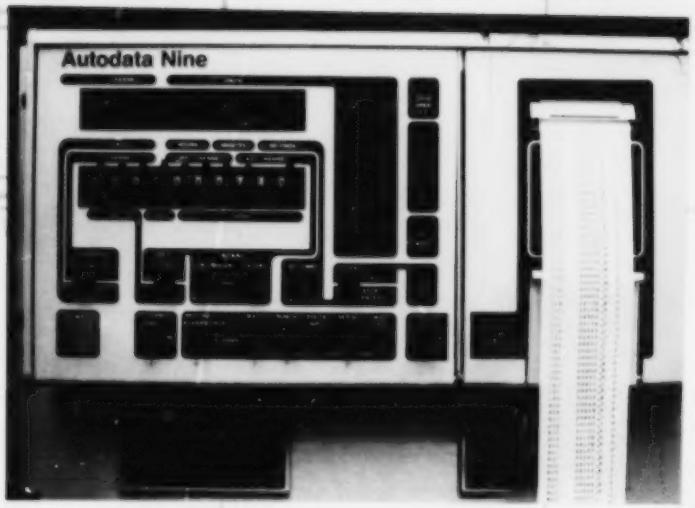
a. COMBINED-CYCLE BUILDING (SOUTH ELEVATION)



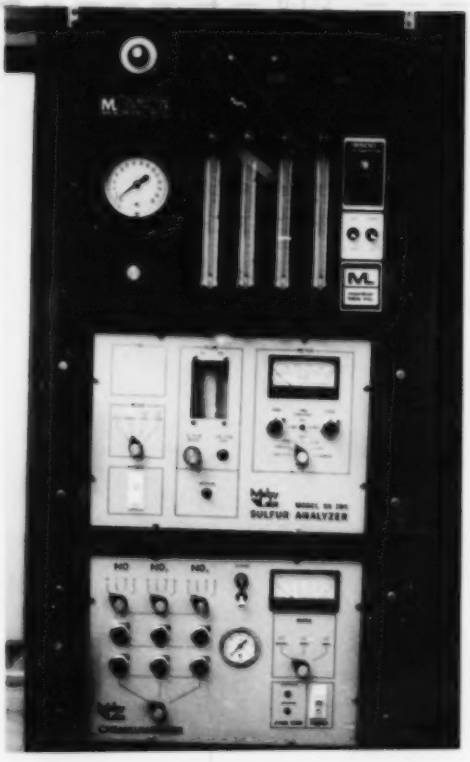
b. DRY COOLING TOWER (WEST ELEVATION)

c. LABORATORY (REFER TO AREA II OF FIGURE 2)

FIGURE 7. PHYSICAL STRUCTURES



a. DATA LOGGER



b. AIR QUALITY ANALYZERS

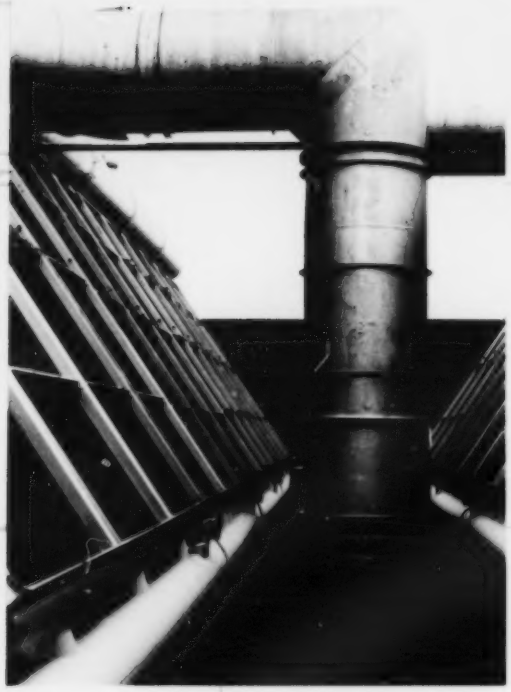
c. METEOROLOGICAL TOWER

FIGURE 8. PERFORMANCE MONITORING EQUIPMENT

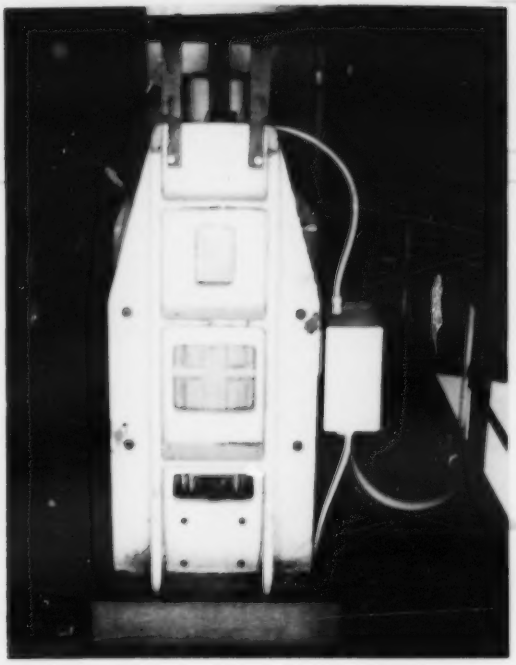
A contract amounting to $3,000 was awarded to VWR Scientific in December, 1976 for laboratory furniture. Equipment located in the laboratory was leased from Radian Corporation and included an atomic absorption spectrophotometer, mass balance, calorimeter, and remote sensing thermometer. Most of this equipment has never been used for fuel or corrosion analyses due to the minimal operation of Potter No. 2 and lack of a qualified technician. The laboratory was provisioned with $7,000 of supplies in 1977.

An equipment installation contract was advertised in March, 1977 for the installation of the meteorological tower, laboratory furniture, thermocouples and pressure transducers on the dry cooling tower (see Figure 9). Condensate thermocouples and flow transmitters on two fuel meters were to be obtained and installed. Additional work included structural, electrical, and mechanical. The thermocouples were similar in specification to those for the dry cooling tower. The flow transmitters were specified to pulse once every 10 gallons and to interface with the existing meters. Modifications to the control panel and to the motor control centers for the dry cooling tower fans were done at a cost of $12,000 in order to provide signals to the data logger (see Figure 10).

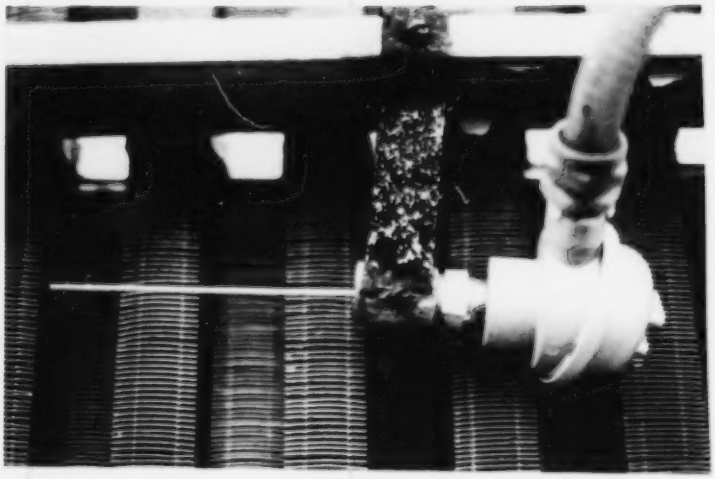
When no acceptable bidders were found for equipment installation, it was decided to proceed using BELD personnel. In June, 1977 the pressure transducers were found to be inadequate for monitoring differentials of less than 0.25 in. H_2O and these were returned to the manufacturer. By the end of 1977, all the performance monitoring equipment was on-site and only the electrical portions of the installation contract remained to be completed. Work was delayed in the spring of 1978 due to a forced outage of the gas turbine. Connections were completed to the data acquisition system in June, 1978.



a. FINTUBE BUNDLES

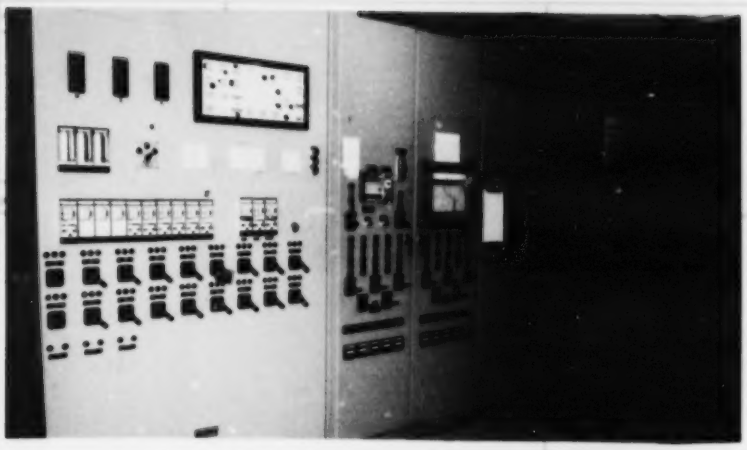


b. FAN PLENUM



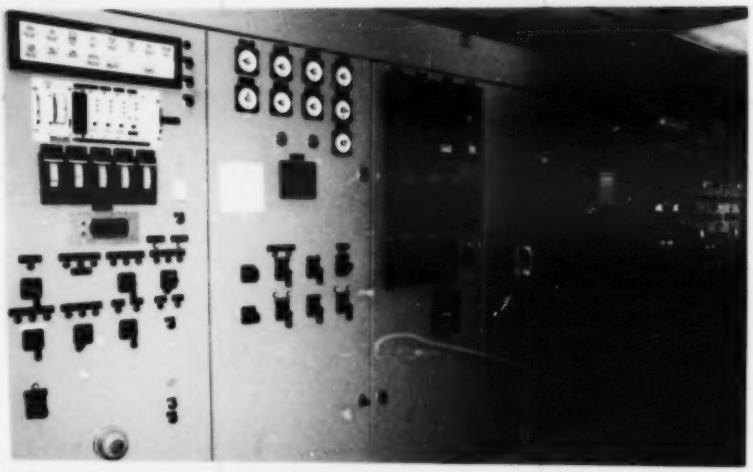
c. THERMOCOUPLE INSTALLATION

FIGURE 9. DRY COOLING TOWER



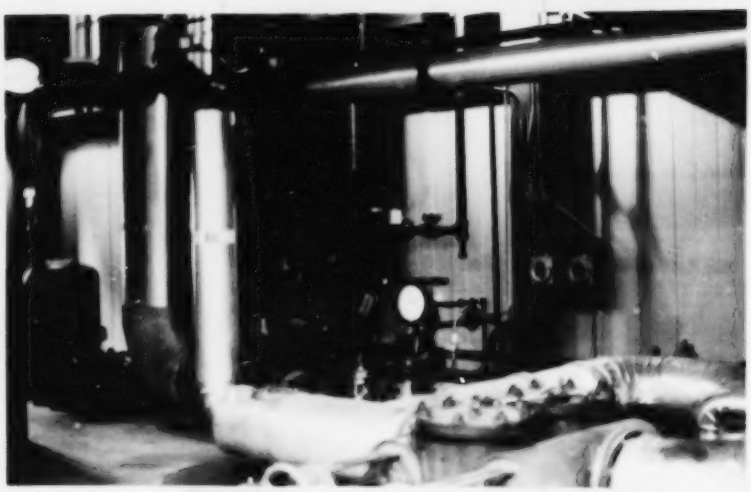
a. NORTH CONTROL PANEL
LEFT TO RIGHT

1. BOILER PANEL
2. CONDENSER PANEL
3. GAS TURBINE PANELS (5)



b. SOUTH CONTROL PANEL
LEFT TO RIGHT

1. STEAM TURBINE PANELS (3)
2. RELAY PANELS (2)
3. AUXILIARY EQUIPMENT CONTROLS
4. ELECTRICAL SYSTEM PANEL



c. FUEL PUMPS AND FILTERS

FIGURE 10. PLANT OPERATION SENSORS

5. DATA COLLECTION/ANALYSIS

All the performance monitoring equipment was installed by June 1978. However, minimal additional operation occurred that year. Table 5 indicates that from April 1979 (when Unit 2 was returned to service following an August 14, 1978 forced outage) through October 1980 about 1200 hours of operation occurred. For that period, data have been obtained and analyzed for some 350 hours as shown in Table 6. The magnetic tape unit was found to be malfunctioning in January 1980 and only data manually obtained by plant personnel (on a schedule of approximately once per hour when the unit is running) are available.

Data on steam parameters, fuel consumption, fan operation, power production and temperatures of air and condensate have been nearly complete. However, both air quality and meteorological data (with the exception of temperature profiles) have been sporadic and of little value. An example of a strip chart scan is shown in Figure 11. With the exception of thermocouple values which are converted by the data logger, additional manipulation is required prior to analyzing performance. Conversion equations for the most important parameters are given in Table 7.

A Fortran computer program has been written to read and analyze the performance data and to echo the input. The program computes an average condensate temperature and corresponding backpressure (based on the GEA expectation of 4°F subcooling), temperature corresponding to the measured backpressure, steam-side duty (based on measured steam flow and an assumed heat of condensation of 1000 Btu/lb), average fan inlet and fintube exhaust temperatures, localized temperature differentials on cell 2A-4, average fan power, air-side duty, theoretical backpressure (based on the GEA performance curves), heat rate, and theoretical heat rate (based on the manufacturer's design values of gas turbine output and fuel consumption vs. temperature, steam turbine output vs. steam flow and backpressure). Tests are also performed to determine variations in local heat transfer on cell 2A-4, recirculation (with possible correlation to low-level winds), same operating power on all fans (only situation for which GEA backpressure is available) and backpressure limits (limited range of steam flow and air temperature). Appendix A contains a program listing and sample input/output.

TABLE 5 GENERATION SUMMARY

Month	Days	Fired Hours	Net Generation (10^3 MW)	Fuel Consumed (10^3 gal)
4/77	5	36	2.1	168
5/77	6	40	2.1	178
6/77	3	12	0.6	51
7/77	7	70	4.9	366
8/77	13	126	8.9	675
9/77	2	11	0.6	49
10/77	4	31	2.2	161
11/77	5	56	4.3	322
12/77	17	212	17.6	1,266
1/78	15	176	15.0	1,075
2/78	5	54	3.8	292
7/78	9	70	5.0	379
8/78	5	31	2.3	180
4/79	8	99	7.3	533
5/79	17	159	11.9	853
6/79	3	35	2.4	180
7/79	10	106	7.2	536
8/79	4	40	2.6	196
9/79	4	51	3.6	263
10/79	4	36	2.1	168
11/79	1	13	1.0	73
12/79	3	26	2.1	150
1/80	18	241	18.8	1,338
8/80	8	70	4.7	313
9/80	4	29	1.7	133
10/80	20	260	21.4	1,507
26	200	2,090	156.2	11,405

TABLE 6 PERFORMANCE MONITORING DATA SUMMARY

Month	Days	Hours
5/79	6	42
6/79	2	12
7/79	5	37
8/79	3	22
1/80	4	28
8/80	4	29
10/80	20	186
7	44	356

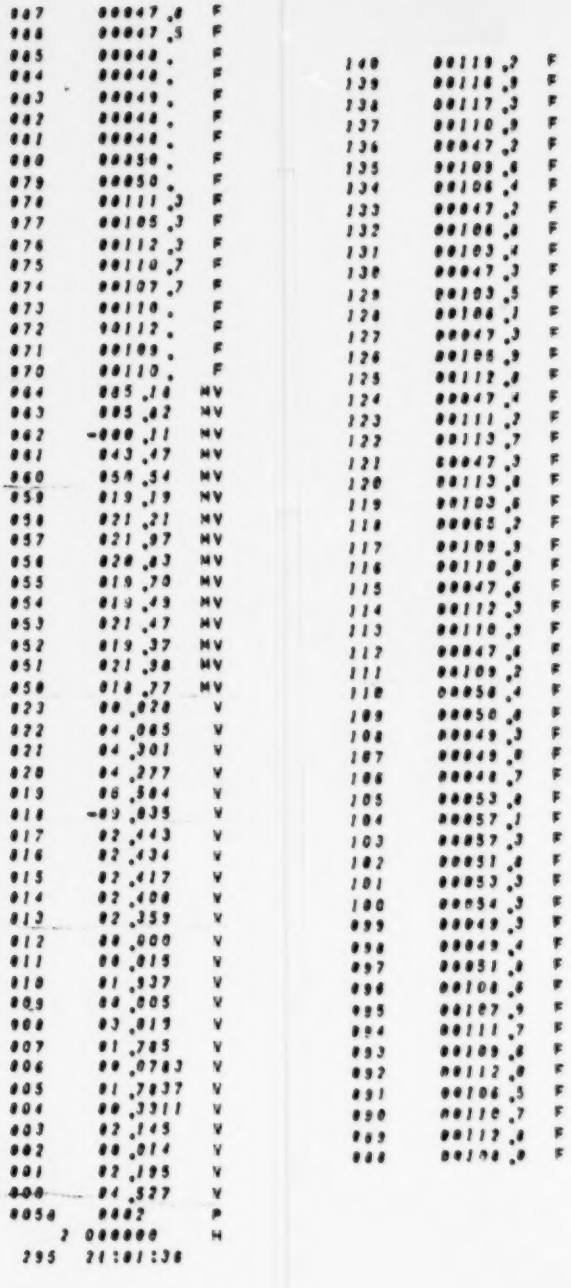


FIGURE 11. TYPICAL STRIP CHART
(OCTOBER 21,1980 JULIAN DAY 295)

TABLE 7 DATA CONVERSION

Channel	Parameter	Conversion From	Conversion To	Conversion Equation
	Chronology	Julian day		
	Time	hr:min:sec		
	Fuel to Combustor	pulse/5 min.	10^6 Btu/hr	x 16.8
	Fuel Leakoff	pulse/5 min.	10^6 Btu/hr	x 16.8
0-12	Meteorology and Air Quality			
13-17	Temperature Profile	volts	°F	x 28.8(-22)
18	Atmospheric Stability			
19	Steam Flow	volts	10^3 lb/hr	(-1) x 62.5
20	Throttle Temperature	volts	°F	(-1) x 250
21	Exhaust Vacuum	volts	in. Hg	(-1) x 7.5
22	Throttle Pressure	volts	$lb/in.^2$	(-1) x 175
23	Air Quality			
50-59	Fan Power	millivolts	kW	x 1.8
60	Steam Turbine Power	millivolts	MW	x 0.42
61	Gas Turbine Power	millivolts	MW	x 1.67
62-63	Auxiliary Power			
64	Net Power	millivolts	MW	x 1.08
70-78	2A-4 Exhaust Temperature - North	°F		
79-87	2A-4 Plenum Temperature - North	°F		
88-96	2A-4 Exhaust Temperature - South	°F		
97-105	2A-4 Plenum Temperature - South	°F		
106-110	2A-4 Fan Inlet Temperature	°F		
111-137	Cell Temperature (in the sequence South Exhaust, Fan Inlet, North Exhaust for Cells 2A-1 through 2A-5, except 2A-4, and 2B-5 through 2B-1)	°F		
138-140	Condensate Temperature	°F		

Example: Exhaust Vacuum (channel 21 from Figure 11)
(4.301 (volts) -1) x 7.5 = 25 in. Hg

6. RESULTS

As was expected from the high capacity factors indicated in Table 5, more than 90 percent of the data have net power values greater than 75 MW with steam flow in excess of 180,000 lb/hr and fans running at full speed. Variations in duty between steam-side cooling and air-side heating are within the range of ± 10 percent. Therefore, the primary influence on steam turbine backpressure is ambient temperature. (The average fan inlet temperature from all 10 cells is considered to be ambient temperature in the following discussion.) The gas turbine flow is essentially a constant volumetric rate, so that as ambient temperature decreases gas turbine power generation increases. Steam production in the heat recovery boiler also increases with decreasing ambient temperature and the condensing duty decreases in difficulty. Consequently backpressure goes down and steam turbine power generation increases. While generation is increasing so is fuel consumption, with the net result that heat rate changes little with ambient temperature. Both design conditions and actual data are presented in Figures 12 through 16 and are discussed below.

BACKPRESSURE

Recorded backpressure measurements (converted from the vacuum readout) at nominal full-load conditions range from 2 to 13 in. Hg absolute. Referring to Figure 4, the high end of this range exceeds the expected range for the dry cooling tower. The data which have been analyzed in this study are presented in Figure 12. Measured backpressure exceeds the GEA estimate by approximately 2 in. Hg in 75 percent of the comparisons. It is also apparent that the performance of the dry cooling tower deteriorates appreciably at ambient temperatures above 60° F. Only limited data were available with the fans run at half-speed and no comparisons were made for the condition.

Data from the plant operator's log indicate that the temperature of steam exhausting the turbine is very close (an average difference of approximately 2° F) to the condensate temperature. This would indicate that GEA's estimate of only 4° F subcooling is correct. Therefore, it was decided that the thermocouple measurement of condensate temperature would be a more accurate means of comparing actual and design backpressure. Figure 13 shows values approximately 1 in. Hg higher than the GEA estimate in 75 percent of the comparisons. The deviation from design values at ambient temperatures above 60° F is also less than that for the measured backpressure data.

While the average fan power is close to design, the average temperature differential across the fintubes is 58° F, compared with the design value of 53° F. This would indicate that air flow is less than design. At present the pitch angle of the fan blades is less than the design value due to the observation by BELD personnel that power consumption by the fan motors was excessive when

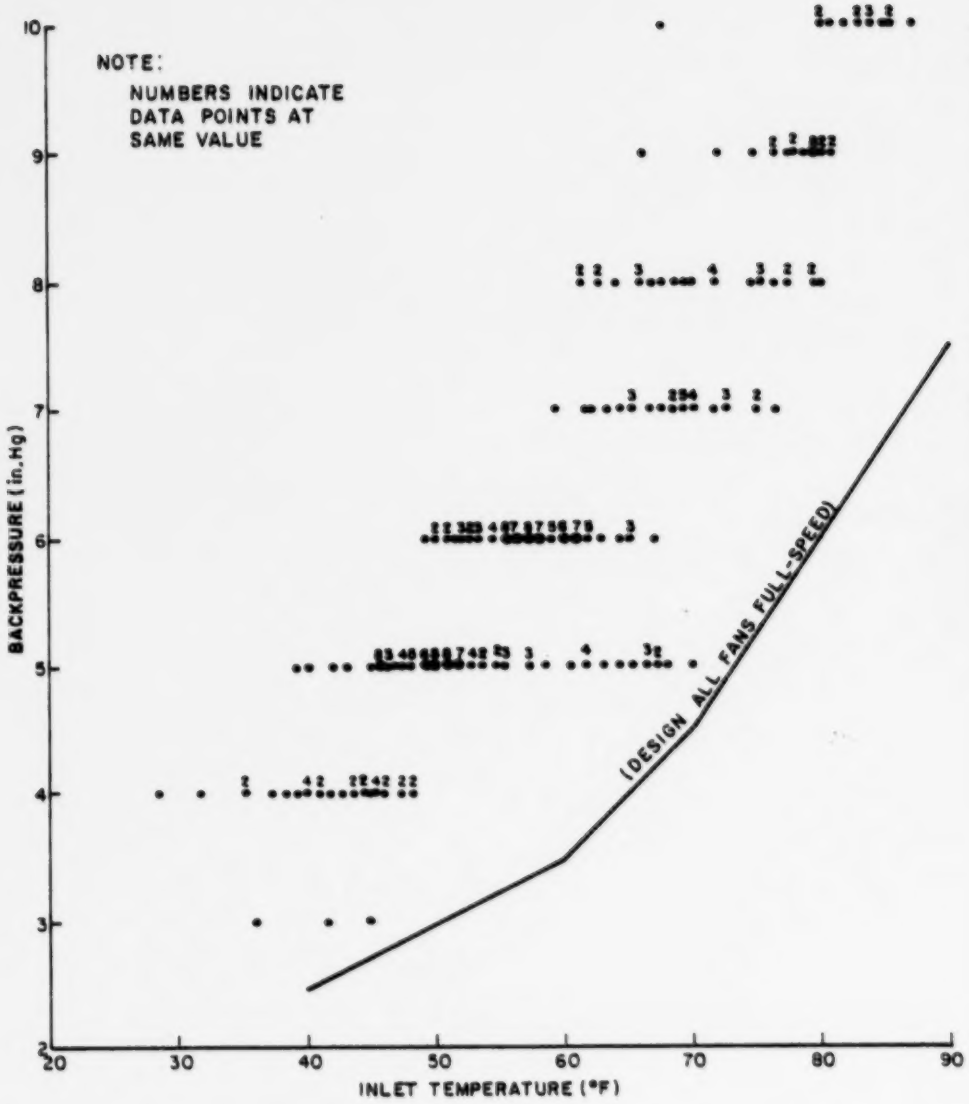


FIGURE 12
VARIATION OF MEASURED BACKPRESSURE
WITH AMBIENT TEMPERATURE

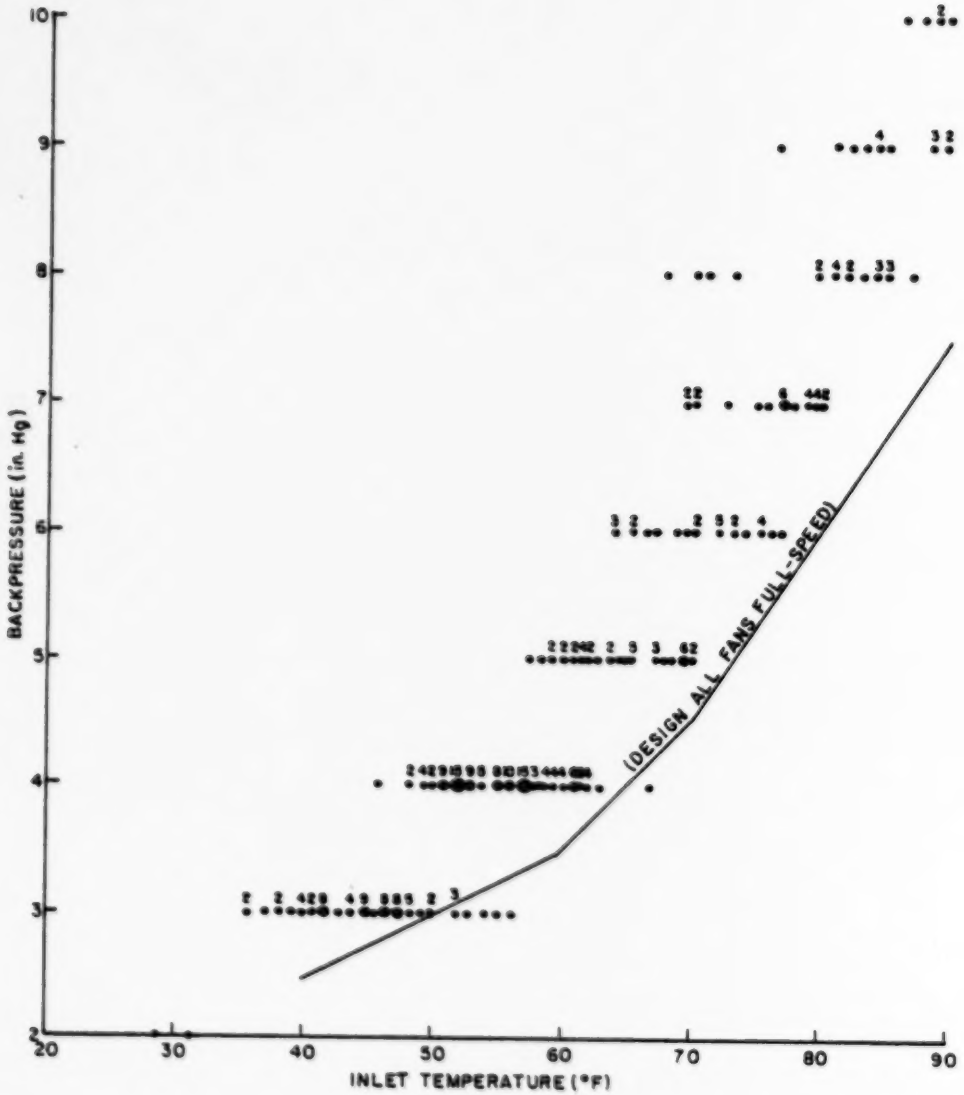


FIGURE 13
VARIATION OF CONDENSATE TEMPERATURE-DERIVED BACKPRESSURE WITH AMBIENT TEMPERATURE

the pitch angle was higher. However, it was also observed that backpressure was closer to design when the pitch angle was higher. It is estimated that a reduction of 1 in. Hg in backpressure would result in approximately a 1 percent increase in steam turbine generator output, or approximately 200 kW. The current fan power consumption is 300 to 400 kW. Therefore, the tradeoff would have to be analyzed with operating data to see if it is worthwhile to optimize the performance of the dry tower by increasing the fan blade angles.

HEAT RATE

Of even greater concern to BELD management is the fact that the unit heat rate exceeds the design value. As demonstrated in Table 2, 1980 operation has been at a higher load and at a lower heat rate than 1979. Figures 14 and 15 compare actual and design values in the two years. As can be seen from the Figures, the design heat rate changes little with ambient temperature. However, it is expected that heat rate increases with elapsed time since major overhaul and with decreased load. The gas turbine combustion temperature also influences heat rate (higher temperatures result in lower heat rates and less time between overhauls) and is monitored by operations personnel. Due to the expected lower efficiency for 1979 operation, it was decided to continue the heat rate analysis only for the 1980 data.

The data in Figure 15 show an average heat rate approximately 1200 Btu/kWh above the design value. The variation at a given ambient temperature is approximately 1000 Btu/kWh. No attempt has been made in this study to explain this variation. In an attempt to explain why the actual heat rate is so far above the design value, a comparison was made of actual and design power generation. As shown in Figure 16, the relationship between the two and with ambient temperature is excellent. It should be noted that data at temperatures below approvimately 32^{o} F were taken in January, 1980, prior to a major equipment failure. This may account for the reduced power output at this time.

Based on the good agreement between design and actual steam flows mentioned earlier, it is thought that the steam turbine generator is performing properly. Since the combined-cycle output is also up to par, operation of the gas turbine generator is acceptable. However, the gas turbine requires more fuel than anticipated. Verification that fuel metering is correct has been obtained from periodic checks on levels in the fuel oil storage tank. Further investigation of compressor air flow and temperatures at various points in the flow path are planned. It may also be that the machine, which is one of the first of its type, is not as efficient as the manufacturer expected.

It should also be mentioned that recent (subsequent to the data analyzed) modifications to the gas turbine combustor have reduced the heat rate by approximately 200 Btu/kWh and increased the gas turbine power output by 2 MW. This modification is only one in a series of fine-tuning steps which may enable the combined-cycle unit to lower its heat rate.

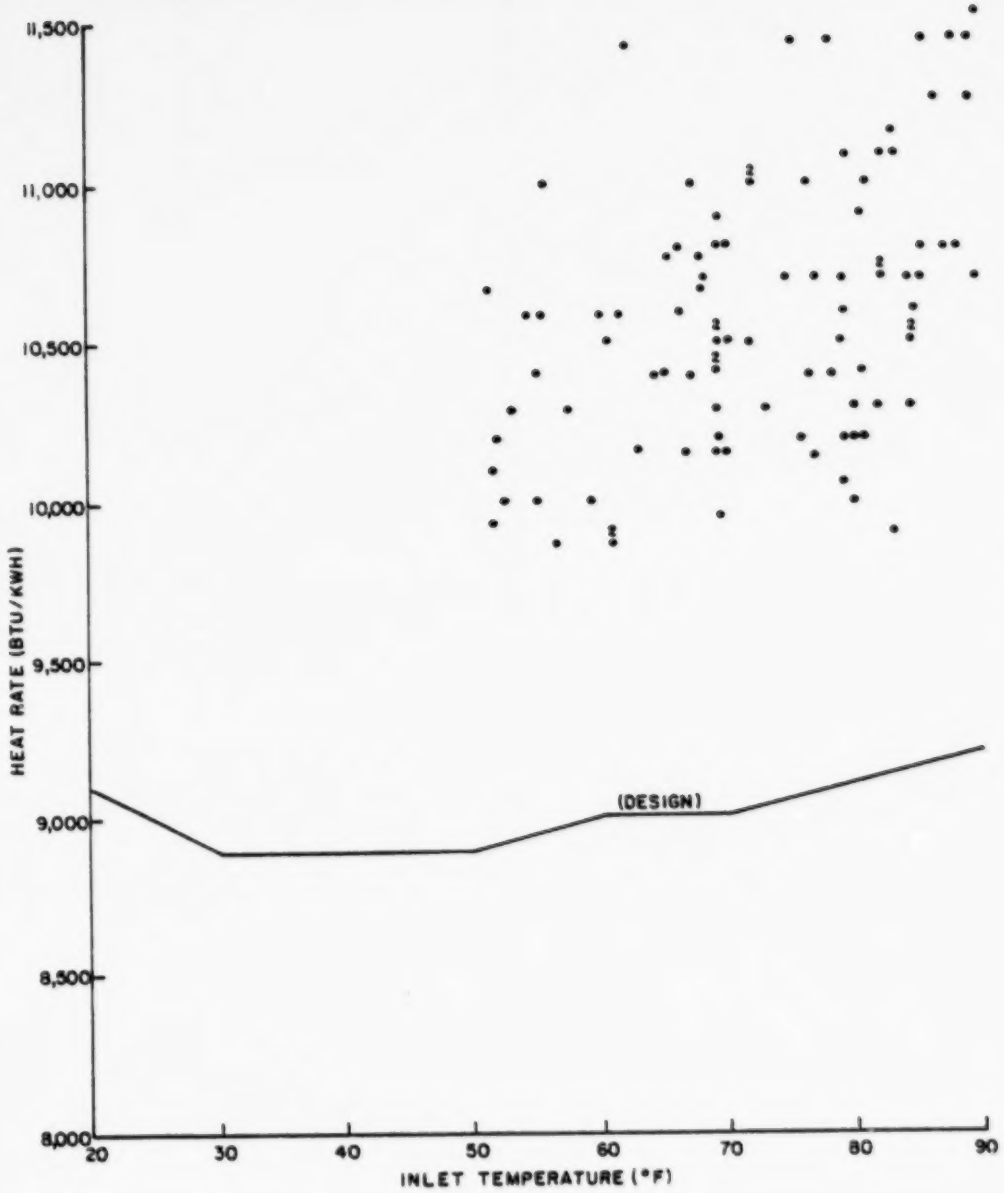


FIGURE 14

VARIATION OF HEAT RATE WITH AMBIENT TEMPERATURE- 1979

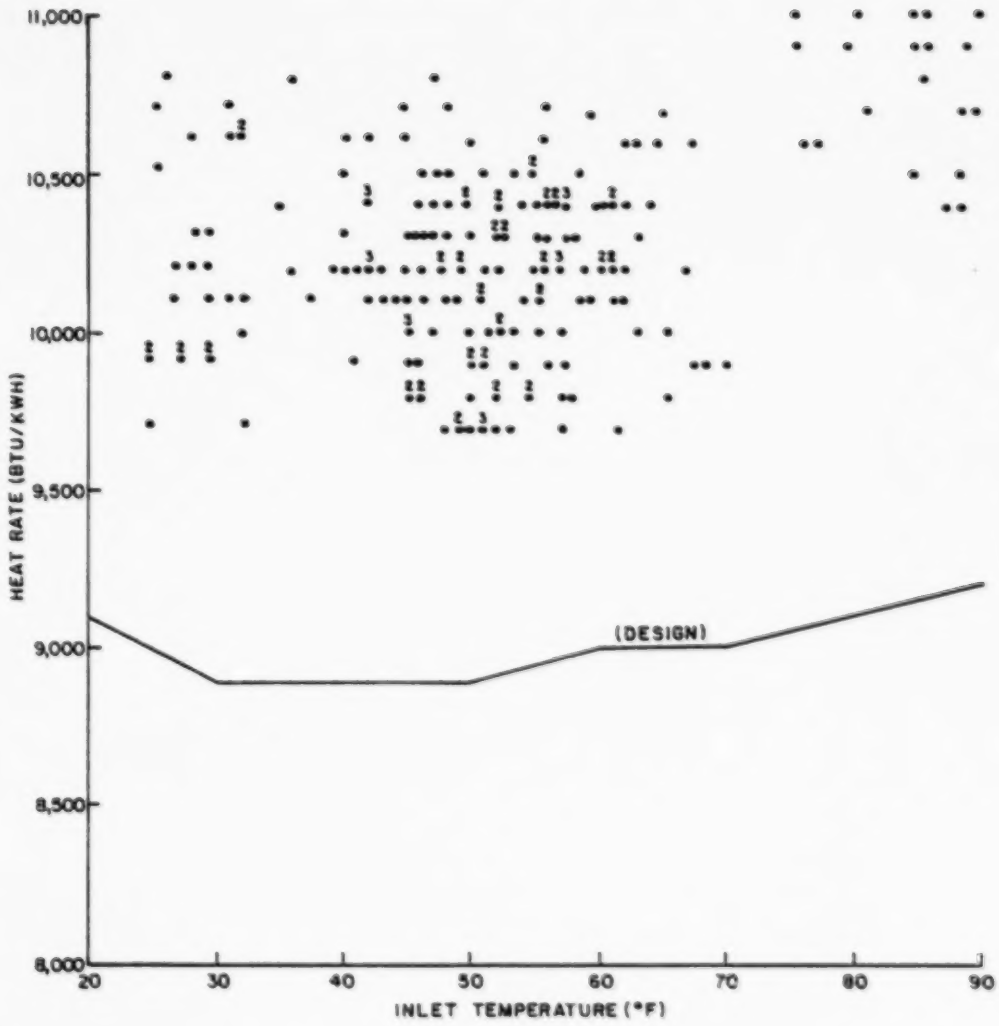


FIGURE 15

VARIATION OF HEAT RATE WITH AMBIENT TEMPERATURE - 1980

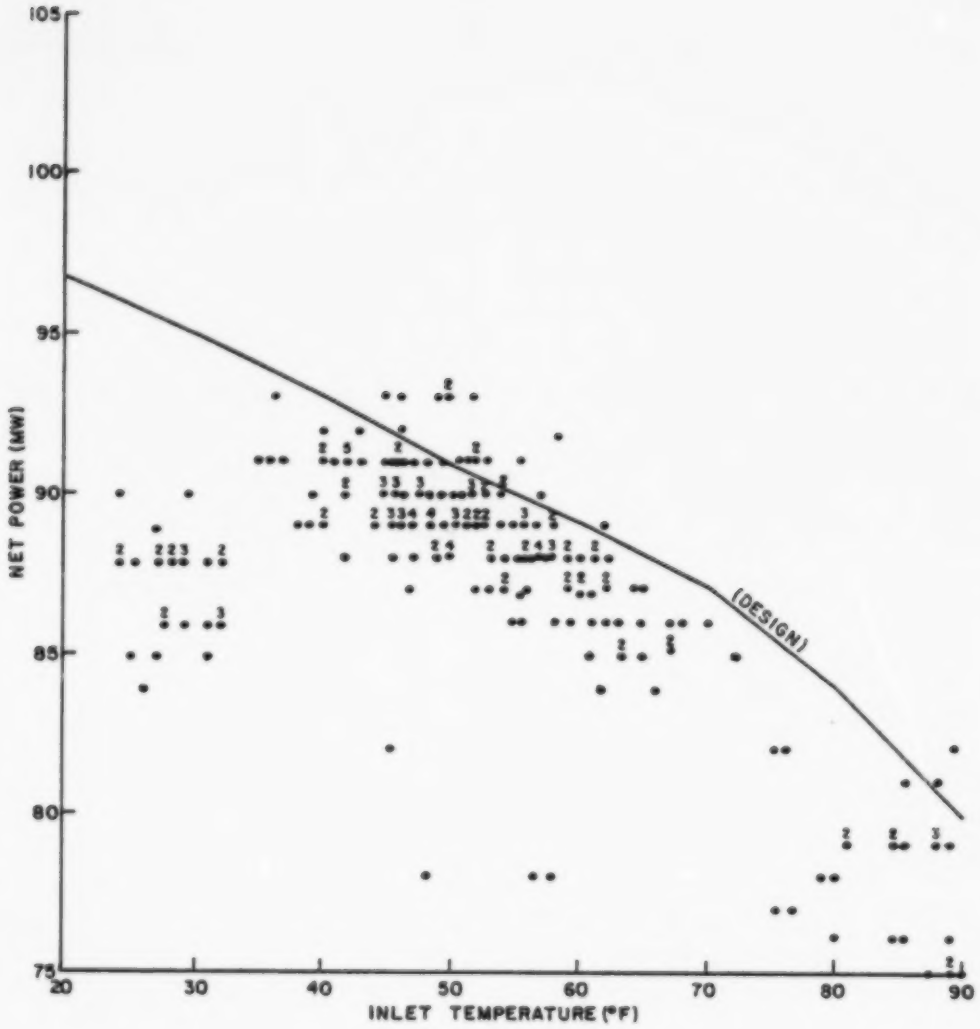


FIGURE 16
VARIATION OF POWER GENERATON
WITH AMBIENT TEMPERATURE – 1980

RECIRCULATION

With regard to the question of recirculation of exhaust air from the dry cooling tower to the fan inlet, analysis of the data indicates that it happens approximately one-third of the time. The recirculation test requires that the temperature at one cell exceed the average of all 10 by more than 5^{o} F. Typically this requirement is met when the temperature at one cell exceeds those adjacent to it by at least 10^{o} F. In all cases the recirculated air is experienced by the A-bank of cells closest to the combined-cycle building (see Figure 6). In most cases, the affected cell is 2A-3, the cell least accessible to ambient air.

As illustrated in Figures 5 and 6, the exhaust steam header passes beneath cell 2A-3 and could increase the inlet air temperature to this cell. However, most of the time this is not the case. Downwash is normally expected to occur when hot exhaust air is forced down by high-velocity winds. The intent of the wind screen around the dry cooling tower is to eliminate this problem by not allowing interaction until the hot plume is consolidated near the top of the fintube bundles. Judging by the lack of recirculation along the outer bank of cells, the wind screen is effective.

Low-level winds (at the 30-ft height on the meteorological tower) were investigated to determine whether any correlation with recirculation exists. The average wind direction is bivariate with azimuth angles of approximately 50 degrees and 210 degrees, approximately perpendicular to the long axis of the dry cooling tower. The range of values in each case is approximately 100 degrees. Thus the wind direction values correspond to a downwash interpretation of the recirculation phenomenon. The average wind speed is approximately 8 mph with more than that amount of variation. By contrast, the expected velocity of hot air exhausting from the fintubes is approximately 5 mph. While the average speed is consistent with expected downwash occurrence, the wide variation discredits this interpretation.

The recirculation is related to the adjacent, higher combined-cycle building. However, a wind-related cause cannot be convincingly demonstrated. Therefore, it is planned to investigate further the flow path of hot air exhausted from the inner bank of cells.

LOCALIZED HEAT TRANSFER

Although not originally designed for that purpose, the localized heat transfer data from cell 2A-4 seem to offer some insight to recirculation occurrences. The temperature differential across the fintubes is almost always greater on the north side than on the south side. Most of the time there is also local variation on the south side. Closer examination has revealed the cause. The plenum air temperature of this cell is highest at the bottom (closest portion of the fintube bundle to the combined-cycle building) and lowest at the apex. Exhaust temperatures are relatively constant leading to the variation in temperature differential. As further evidence of this phenomenon, the shroud temperatures (measured below the fan) are also highest on the building side.

The data suggest that, at least on the building side of the A-bank of cells, heat transfer across the lower portion of the fintubes is impeded by recirculation. The exact path of this recirculation has not been determined. Otherwise, heat transfer across the fintubes appears to be uniform and in accordance with design.

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2. R. W. Beck and Associates, "Research on Dry-Type Cooling Towers for Thermal Electric Generation," Parts I and II, for the Water Quality Office of the Environmental Protection Agency, November, 1970. 16130EES.

3. Armstrong, C. H. and Newton, D. H., "Startup and Initial Operating Experience of Braintree's 85-Megawatt Combined-Cycle Unit," ASME Paper No. 77-JPGC-GT-1, September, 1977.

4. Henderson, M. D. "Feasibility Study for a Direct, Air-Cooled Condensation System," for the Office of Energy, Minerals and Industry of the Environmental Protection Agency, publication EPA-600/2-76-178, July, 1976.

APPENDIX A
COMPUTER PROGRAM

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FILECOPY/3000 (4.1) R.W. BECK & ASSOC., SEATTLE
BELD2.EPSMC.CC6135                    WED, DEC  3, 1980,  3:39 PM


$CONTROL INIT,USLINIT,LOCATION                                          00001000
      PROGRAM BELD2                                                     00002000
C     THE BELD2 PROGRAM WAS WRITTEN BY MDH IN OCTOBER,1980 TO ANALYZE   00003000
C     DATA RECORDED BY THE DATA LOGGER ADJACENT TO THE DRY TOWER. INPUTS00004000
C     READ IN INCLUDE CHRONOLOGY AND FUEL FLOW, METEOROLOGY FROM A NEAR-00005000
C     BY TOWER AND AIR QUALITY, STEAM PARAMETERS, FAN POWER, COMBINED-  00006000
C     CYCLE GENERATION, LOCALIZED HEAT TRANSFER ON 1 OF 10 CELLS, OVER- 00007000
C     ALL HEAT TRANSFER ON THE OTHER 9 CELLS AND CONDENSATE TEMPERATURE.00008000
C     THE PROGRAM IS SET UP TO ECHO INPUT DATA, INVESTIGATE SUBCOOLING, 00009000
C     COMPUTE STEAM AND AIR DUTIES, INVESTIGATE SUN AND SURFACE LOCATION00010000
C     EFFECTS, ANALYZE RECIRCULATION, COMPUTE THEORETICAL BACKPRESSURE, 00011000
C     AND COMPARE ACTUAL AND THEORETICAL HEAT RATES.                    00012000
      DIMENSION MET(13),TEMP(5),STEAM(6),FANP(10),POWER(5),LOCNE(9),LOCN00013000
     ,P(9),LOCSE(9),LOCSP(9),SHROUD(5),TC(9,3),CONDT(3),DELTN(9),DELTS( 00014000
     .9)                                                                00015000
      REAL MET                                                          00015100
 1000 READ(5,*,END=9999)IDATE,IHOUR,IFUEL,ILEAK                         00016000
      READ(5,*)(MET(I),I=1,13)                                          00017000
      READ(5,*)(TEMP(I),I=1,5)                                          00018000
      READ(5,*)(STEAM(I),I=1,6)                                         00019000
      READ(5,*)(FANP(I),I=1,10)                                         00020000
      READ(5,*)(POWER(I),I=1,5)                                         00021000
      READ(5,*)(LOCNE(I),I=1,9)                                         00022000
      READ(5,*)(LOCNP(I),I=1,9)                                         00023000
      READ(5,*)(LOCSE(I),I=1,9)                                         00024000
      READ(5,*)(LOCSP(I),I=1,9)                                         00025000
      READ(5,*)(SHROUD(I),I=1,5)                                        00026000
      READ(5,*)((TC(I,J),J=1,3),I=1,3)                                  00027000
      READ(5,*)((TC(I,J),J=1,3),I=4,6)                                  00028000
      READ(5,*)((TC(I,J),J=1,3),I=7,9)                                  00029000
      READ(5,*)(CONDT(I),I=1,3)                                         00030000
      IF(TEMP(1)-5.)41,41,42                                            00031000
   41 TEMP(1) = TEMP(1)*28.8-22.                                        00032000
   42 WRITE(6,100)IDATE,IHOUR,TEMP(1)                                   00033000
  100 FORMAT(%14C,' JULIAN DATE',I5,5X,' HOUR',I5,5X,' AMB TEMP',I5,    00034000
     .' DEG F'/)                                                        00035000
      AVCT = 0.                                                         00036000
      DO 1 I = 1,3                                                      00037000
    1 AVCT = AVCT + CONDT(I)/3.                                         00038000
      VP = EXP((AVCT-66.)/40.)                                          00039000
C     APPROXIMATE RELATIONSHIP BETWEEN TEMPERATURE AND VAPOR PRESSURE   00040000
      TBP = 30. -(STEAM(4)-1.)*7.5                                      00041000
      TTBP = 70.+40.*LOG(TBP)                                           00042000
      QSTM = (STEAM(2)-1.)*62.5                                         00043000
      WRITE(6,101)AVCT,VP                                               00044000
  101 FORMAT(' COND TEMP',I5,' DEG F',5X,' BACKPRESS CORRES',I5,' IN HG'00045000
     ./)                                                                00046000
      WRITE(6,102)TBP,TTBP                                              00047000
  102 FORMAT(' TURB BACKPRESS',I5,' IN HG',5X,' TEMP CORRES',I          00048000
     .5,' DEG F'/)                                                      00049000
      WRITE(6,201)QSTM,QSTM                                             00050000
  201 FORMAT(' STEAM FLOW',I5,' THOU LB/HR',5X,' STEAM DUTY',I5,' MM BTU00051000
     ./HR'/)                                                            00052000
      TIN = 0.                                                          00053000
      DO 2 I = 1,9                                                      00054000
    2 TIN = TIN + TC(I,2)                                               00055000
      TIN = (TIN+SHROUD(3))/10.                                         00056000
      TOUT = 0.                                                         00057000
      DO 6 I = 1,9                                                      00058000
```

```
      6 TOUT = TOUT + TC(I,1)+TC(I,3)                                   00059000
        TOUT = (TOUT+LOCNE(5)+LOCSE(5))/20.                             00060000
        WRITE(6,202)TIN,TOUT                                            00061000
    202 FORMAT(' INLET TEMP',I5,' DEG F',5X,' OUTLET TEMP',I5,' DEG F')  00062000
        DO 51 I =1,9                                                    00063000
        DELTN(I) = 0.                                                   00064000
     51 DELTS(I) = 0.                                                   00065000
        DO 52 I = 1,9                                                   00066000
        DELTN(I) = LOCNE(I)-LOCNP(I)                                    00067000
     52 DELTS(I) = LOCSE(I) - LOCSP(I)                                  00068000
        DELTNA = 0.                                                     00069000
        DELTSA = 0.                                                     00070000
        DO 53 I = 1,9                                                   00071000
        DELTNA = DELTNA + DELTN(I)/9.                                   00072000
     53 DELTSA = DELTSA + DELTS(I)/9.                                   00073000
        WRITE(6,109)DELTNA,DELTSA                                       00074000
    109 FORMAT(' DELTA T NORTH SIDE OF 2A-4',I5,' DEG F',5X,'DELTA T SOUTH00075000
       . SIDE OF 2A-4',I5,' DEG F')                                     00076000
        DO 54 I = 1,9                                                   00077000
        TEST = ABS(DELTNA-DELTN(I))                                     00078000
        IF(TEST-5.)54,54,62                                             00079000
     54 CONTINUE                                                        00080000
        GO TO 61                                                        00081000
     62 WRITE(6,110)                                                    00082000
    110 FORMAT(' VARIATION IN LOCAL HEAT TRANSFER ON NORTH SIDE')       00083000
     61 DO 55 I = 1,9                                                   00084000
        TEST = ABS(DELTSA-DELTS(I))                                     00085000
        IF(TEST-5.)55,55,64                                             00086000
     55 CONTINUE                                                        00087000
        GO TO 63                                                        00088000
     64 WRITE(6,111)                                                    00089000
    111 FORMAT(' VARIATION IN LOCAL HEAT TRANSFER ON SOUTH SIDE')       00090000
     63 DO 3 I = 1,9                                                    00091000
        IF(TC(1,2)-TIN-5)3,3,4                                          00092000
      3 CONTINUE                                                        00093000
        IF(SHROUD(3)-TIN-5.)5,5,4                                       00094000
      4 WRITE(6,103)                                                    00095000
    103 FORMAT(' RECIRCULATION OCCURRED')                               00096000
C       RECIRCULATION MAY BE CAUSED BY HIGH WINDS                       00097000
        WD = MET(8)*108.                                                00098000
        IF(WD-360.)71,71,72                                             00099000
     72 WD = WD-360.                                                    00100000
     71 WS = MET(7)*20.                                                 00101000
        WRITE(6,112)WD,WS                                               00102000
    112 FORMAT(' WIND DIRECTION',I5,' DEG',5X,' WIND SPEED',I5,' MPH')  00103000
      5 AFANP = 0.                                                      00104000
        DO 7 I=1,10                                                     00105000
      7 AFANP = AFANP+FANP(I)*1.8/10.                                   00106000
        DO 8 I=1,10                                                     00107000
         ATEMP = ABS(FANP(I)-AFANP/1.8)                                 00108000
        IF(ATEMP-10.)8,8,9                                              00109000
      8 CONTINUE                                                        00110000
        GO TO 10                                                        00111000
      9 WRITE(6,104)                                                    00112000
    104 FORMAT(' FANS ARE NOT ALL AT SAME SPEED')                       00113000
        GO TO 32                                                        00114000
C       APPROXIMATE VOLUMETRIC FLOW RATES FOR VARIOUS FAN SPEEDS (PITCH 00115000
C       ADJUSTED) ACCORDING TO GEA PROPOSAL                             00116000
     10 IF(AFANP-25.)14,15,15                                           00117000
     14 IF(AFANP-3.)16,17,17                                            00118000
     15 VOLF = 1500.                                                    00119000
        GO TO 18                                                        00120000
     17 VOLF = 750.                                                     00121000
        GO TO 18                                                        00122000
     16 VOLF = 300.                                                     00123000
     18 GAIR = 0.04*VOLF*30.*(TOUT-TIN)/(460.+TIN)                      00124000
```

```
C     APPROXIMATE RELATIONSHIP BETWEEN BACKPRESSURE, STEAM FLOW AND      00125000
C     AMBIENT TEMPERATURE ACCORDING TO GEA PROPOSAL                      00126000
      IF(VOLF-750.)26,27,28                                              00127000
   28 TCHK = 30.+(250.-QSTM)*.35                                         00128000
      IF(TIN-TCHK)32,30,30                                               00129000
   30 BP = (TIN-30.)*(QSTM-50.)/1000.                                    00130000
      GO TO 29                                                           00131000
   27 TCHK = 30.+(250.-QSTM)*.35                                         00132000
      IF(TIN-TCHK)31,31,32                                               00133000
   31 TCHK = 10.+(200.-QSTM)*.51                                         00134000
      IF(TIN-TCHK)32,33,33                                               00135000
   33 BP = (TIN+20.)*(QSTM-20.)/1500.-1.                                 00136000
      GO TO 29                                                           00137000
   26 TCHK = 10.+(110.-QSTM)*1.2                                         00138000
      IF(TIN-TCHK)34,34,32                                               00139000
   34 TCHK = 10.+(60.-QSTM)*1.3                                          00140000
      IF(TIN-TCHK)32,37,37                                               00141000
   37 BP = TIN*(QSTM-30.)/300.+3.                                        00142000
      GO TO 29                                                           00143000
   32 WRITE(6,105)                                                       00144000
  105 FORMAT(' GEA BACKPRESSURE CANNOT BE ESTIMATED'/)                   00145000
      QAIR=0.                                                            00146000
      BP=0.                                                              00147000
C     FUEL VALUES ARE GIVEN IN TENS OF GALLONS PER FIVE MINUTES, NO. 2   00148000
C     FUEL OIL HAS A HHV OF 140,000 BTU PER GALLON                       00149000
   29 IF(POWER(5))80,80,81                                               00149100
   80 POWER(5) = 0.01                                                    00149200
   81 HR = (IFUEL-ILEAK)*16800./(POWER(5)*1.08)                          00150000
      NMW = POWER(5)*1.08                                                00151000
      GTMW = POWER(2)*1.67                                               00152000
      STMW = POWER(1)*.42                                                00153000
C     APPROXIMATE RELATIONSHIP BETWEEN GT POWER, FUEL INPUT AND AMBIENT  00154000
C     TEMPERATURE; ST POWER AND FLOW AND BACKPRESSURE ACCORDING TO TBD   00155000
C     CALCULATIONS                                                       00156000
      TGTMW = 83.-0.22*TIN                                               00157000
      TSTMW = 0.11*QSTM*(1.-0.02*(TBP-3.))                               00158000
      TFI = 880.-2.23*(TIN-20.)                                          00159000
      THR = TFI*1000./(TGTMW+TSTMW)                                      00160000
      WRITE(6,204)AFANP,QAIR                                             00161000
  204 FORMAT(' AV FAN POWER',I5,' KW',5X,' AIR DUTY',I5,' MM BTU/HR'/)   00162000
      WRITE(6,205)BP                                                     00163000
  205 FORMAT(' GEA BACKPRESSURE',I5,' IN HG'/)                           00164000
      WRITE(6,106)HR,NMW                                                 00165000
  106 FORMAT(' HEAT RATE',I8,' BTU/NET KWH',5X,' NET GENERATION',I5,' MW00166000
     .'/)                                                                00167000
      WRITE(6,108)THR                                                    00168000
  108 FORMAT(' TBD HEAT RATE',I8,' BTU/GROSS KWH'/)                      00169000
      WRITE(6,107)GTMW,STMW                                              00170000
  107 FORMAT(' GT GROSS POWER',I5,' MW',5X,' ST GROSS POWER',I5,' MW'/)  00171000
      GO TO 1000                                                         00172000
 9999 STOP                                                               00173000
      END                                                                00174000
```

JULIAN DATE 295 HOUR 21 AMB TEMP 46 DEG F

COND TEMP 117 DEG F BACKPRESS CORRES 4 IN HG

TURB BACKPRESS 5 IN HG TEMP CORRES 136 DEG F

STEAM FLOW 210 THOU LB/HR STEAM DUTY 210 MM BTU/HR

INLET TEMP 49 DEG F OUTLET TEMP 108 DEG F

DELTA T NORTH SIDE OF 2A-4 41 DEG F DELTA T SOUTH SIDE OF 2A-4 57 DEG F

VARIATION IN LOCAL HEAT TRANSFER ON SOUTH SIDE

RECIRCULATION OCCURRED

WIND DIRECTION 192 DEG WIND SPEED 1 MPH

AV FAN POWER 36 KW AIR DUTY 210 MM BTU/HR

GEA BACKPRESSURE 3 IN HG

HEAT RATE 10300 BTU/NET KWH NET GENERATION 91 MW

TRD HEAT RATE 8800 BTU/GROSS KWH

GT GROSS POWER 72 MW ST GROSS POWER 21 MW

```
295 21    58 2
4.52 2.19 0.01 2.14 0.33 1.78 0.07 1.78 3.01 0.05 1.93 0.01 0
2.35 2.40 2.41 2.43 2.44
0 6.58 4.27 4.30 4.06 0.02
18 21 19 21 19 19 20 21 21 19
50 43 0 5 85
110 109 112 110 107 110 112 105 111
50 50 48 48 49 48 48 47 47
108 112 110 106 112 109 111 107 108
51 49 49 54 53 51 57 57 53
48 49 49 50 58
109 47 110 112 47 110 109 65 103
113 47 113 111 47 112 105 47 106
103 47 103 106 47 106 109 47 110
117 116 119
```

APPENDIX B

NOISE

Two sampling programs were conducted on November 13 and 14, 1980. All readings were performed using ANSI Type 1 equipment which included the following:

a) General Radio Model GR1933 Sound Level, Analyzer with full octave band capacity (SN 635).

b) Uher Model 4000 Report Tape Recorder (SN 035863).

c) General Radio Model GR1562A Acoustic Calibrator (SN 13732).

All equipment carries current calibration, traceable to National Bureau of Standards.

In operation, the sound pressures are collected by a single microphone and fed into the GR1933 analyzer. An AC output from the GR1933 is fed into the Uher tape recorder for statistical analysis at a later date. The signal received by the tape recorder is "Flat" or unweighted, but has been amplified uniformly to fit the tape recorder's input response. The analyzer was also used independently to determine weighted and unweighted noise components.

A monitoring site approximately 200 feet from the turbine building was selected. This site provided good reception of noise generated by the turbine equipment and dry cooling tower. It also provided worst-case property line data. Noise levels from this site are higher than those which might be experienced at a residence in the area. Receptor impact can be calculated using these data. The first sampling program was designed to determine the fluctuations in "A"-weighted levels during the startup period. The existing minimum background level was found to be approximately 52-53 db(A). The variations of noise during startup are shown in Table B-1. This table also shows the calculated contribution of the dry cooling tower and combined-cycle equipment. The last entry in this table is the steady state noise level at full load.

Table B-2 details the minimum and maximum values gathered during the 11/14/80 sampling session. For each of the eight major octave bands and an A-weighted composite, the ambient levels, full load levels and calculated equipment contributions are shown.

The original specifications for the dry cooling tower alone are detailed in Table B-3. These levels were specified at a distance of 400 feet. The measurements made on 11/13/80 and 11/14/80 were at a distance of 200 feet; these data include the contribution of both dry cooling tower and generating unit. Due to operating constraints, the dry cooling tower could not be operated independently

TABLE B-1

A-WEIGHTED[a] NOISE LEVELS DURING STARTUP (11/13/80)

Time	Measured Noise Level (db)	Calculated Equipment Noise Level (db)	Comments
0725	53	0	Equipment Off
0734	55	50	Turbine starting motor on
0735	56	52	
0737	58	56	Starting motor off
0738	59	57	
0739	61	60	
0741	61	60	Bleed valves close/on line
0743	61	60	
0750	63	63	
0751	67	67	Steam valve opened and closed
0751:30	69	69	
0751:50	70	70	
0752:10	71	71	
0753:30	68	68	
0754	70	70	
0754:30	66	66	
0755	65	65	
0755:20	66	66	
0755:40	67	67	
0756	64	64	
0756:20	64	64	
0813:40	70	70	Diesels On
0814	69	69	
0819	72	72	
0821	69	69	
0821:30	72	72	
0823:40	62	61	Steam Turbine On/Dump Valve
0828:30	61	60	Starting to close
0830	60	59	

[a]Reference 20 micronewtons per meter squared

TABLE B-2

COMPARISON OF BACKGROUND AMBIENT AND EQUIPMENT SOUND PRESSURE LEVELS (SPL)
(Equiment At Full Load)

Frequency (Hz)	Ambient Min. (db)	Ambient Max. (db)	Measured @ 200 ft Min. (db)	Measured @ 200 ft Max. (db)
63	68	74	79	85
125	65	71	79	82
250	62	67	58	63
500	57	61	60	64
1000	59	55	54	56
2000	52	57	49	51
4000	41	40	42	44
8000	not available		not available	
A-Weighted	50	52	61	62

TABLE B-3

COMPARISON OF MAXIMUM MEASURED AND SPECIFIED SOUND PRESSURE LEVELS (SPL)
(Equipment at Full Load)

Frequency (Hz)	Measured (db) @ 200 ft	Correction (db) to 400 ft	Atmospheric Attenuation (db)	SPL (db) @ 400 ft	Specification (db) @ 400 ft
63	85	-6	0	79	69
125	82	-6	0	76	62
250	63	-6	-0.1	56.9	55
500	64	-6	-0.2	57.8	50
1000	56	-6	-0.3	49.7	48
2000	51	-6	-0.7	44.3	46
4000	44	-6	-1.4	36.6	44
8000	not available	-6	-2.7	not available	42
A-weighted	59	-6	(a)	53	51

(a) Unknown for A-weighted composites

to determine its contribution. As an approximation, if the dry cooling tower and combustion turbine are assumed to produce exactly the same noise levels in each frequency band, then the levels shown in Table B-3 (SPL @ 400 ft) could be reduced 3 db. Comparing these reduced 400 ft levels with the original specifications for the dry cooling tower, the dry tower is found to be in compliance at frequencies above 500 Hz and in an A-weighted mode.

Massachusetts regulations limit noise from new sources (measured at the property line) as follows: a maximum increase of 10 db(A), and no introduction of "pure tones". A puretone condition exists when an A-weighted octave band level exceeds (both) its neighbors by 3 db or more.

Table B-4 converts the predicted 400 ft levels from Table B-3 to A-weighted octave bands and identifies pure tone introductions. Table B-4 also identifies any pure tone conditions that existed prior to the addition of Potter 2. The results of Table B-4 show that Potter 2 causes an acceptable overall increase of 3 db(A) at the property line at the time of testing. Potter 2 creates pure tone conditions at 125 Hz and 500 Hz which violate state noise regulations at the property line.

The noise studies can be summarized as follows: the dry cooling tower complied with the original specifed levels above 500 Hz and the total plant complied with state regulations for total allowable "A"-weighted increases but violated pure tone restrictions at 125 and 500 Hz.

TABLE B-4

COMPARISON OF NOISE LEVELS AND MASSACHUSETTS REGULATIONS

Frequency (Hz)	Existing Ambient SPL (db)	"A" Correction (db)	Existing Ambient "A"-weighted (db)	Predicted SPL (db) @ 400 ft	"A" weighted (db) @ 400 ft
63	68	-26	42	79	53
125	65	-16	49	76	60(b)
250	62	-9	53	56.9	47.9
500	57	-3	54	57.8	54.8(b)
1000	59	0	59 (a)	49.7	49.7
2000	52	+1	53	44.3	45.3
4000	41	+1	42	36.6	37.6
8000	not available	-1	-	not available	-
A-weighted	50	N/A	50	53	53

(a) Existing pure tone - no violation of state noise regulations

(b) Pure tone introduced - violation of state noise regulations

APPENDIX C

AIR QUALITY

Air quality data have been reported for ambient concentrations of total suspended particulates (TSP), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2).

Two General Metal Works No. 2000 high volume air samplers were used to measure TSP. The samplers were calibrated against an orifice unit. The data reported for 1973 for SO_2 and NO_2 were obtained using wet-chemistry methods of detection. Subsequent SO_2 data were monitored by the Meloy Model SA-285 analyzer. The analyzer was audited using a Bendix Model 8861 permeation and dilution air portable calibration unit. Subsequent NO_2 data were monitored by the Meloy Model NA-520-2 NO-NO_x analyzer. The Bendix 8861 was also used to audit the NO-NO_x analyzer. A cylinder of NO in oxygen-free nitrogen was used for calibration.

The total suspended particulates were sampled at four locations near the Potter Generating Station and the results are presented below:

Year	No. of Samples	Average 24-hr Concentration ($\mu g/m^3$)
1973	14	92
1974	39	55
1975	22	54
1976	7	55
1980	12	86

The sulfur dioxide data are presented below. It should be noted, however, that concentrations approaching the 24-hour standard of 365 $\mu g/m^3$ were observed in early October 1980.

Year	No. of Samples	Average 24-hr Concentration ($\mu g/m^3$)
1973	14	35
1979	5	34
1980	15	133

The nitrogen dioxide data are presented below:

Year	No. of Samples	Average 24-hr Concentration ($\mu g/m^3$)
1973	14	80
1980	8	30

APPENDIX D

CORROSION

Galvanized fintubes were selected for the dry cooling tower based on inspections of various units in the U. S. and Europe. It was observed that the original bright shiny surface turned dull to dark grey over a period of years. Scraping this surface revealed shiny zinc beneath. Rust coloring on these tubes could be scraped off and appeared to be an external stain rather than an oxide of the base metal fin material.

The Braintree tower was inspected during November, 1980. It is generally in very good condition, tubes are dull rather than shiny but have not yet begun to darken like some of the older units observed in Europe. Fins which have been physically scraped or cut show rust where the zinc has been cut through to the base metal. The extent of this is minor.

The dephlegmator (counter flow of steam and condensate, located centrally in the A-frame structures) sections look rusty underneath the steam headers. This color can be scaped off to reveal shiny zinc beneath. This coloring is probably from rust washing off the steam pipe that lies above the INSIDE bank of each dephlegmator section. This pipe was rusty for some time after erection before it was painted. There is no rust color on the OUTSIDE bank of the dephlegmator section.

One place was found where the galvanizing appears to be blistering up due to oxidizing of the material below (a single tube for a length of about 8"). Both adjacent tubes were in good condition. Since each tube is galvanized singly before being welded into the bundle,it is likely that this one tube had some oil or grease on it that did not come off in the pickling process that is performed just prior to galvanizing. Thus the zinc did not bond to this one area of this one tube.

Even though the unit has seen limited operation (and a cold unit is expected to be more susceptible to corrosion than an operating unit), there is no sign of external corrosion of fintubes that might affect its performance or its longevity.

The inside of tubes and steam pipes is regular carbon steel. After the unit has been idle for some time, the operators wash the inside of the tubes with a fire hose to flush out iron oxide. This reduces the time necessary to clean the boiler water after startup. Thus the inside of the unit is subject to oxidation, especially when it is idle.

Very little buildup of dirt, bugs, etc. is evident on the inside of the A-frame.

APPENDIX E

CONVERSION FACTORS

Length: 1 in. = 2.54 centimeter
1 ft = 0.305 meter

Volume: 1 gallon = 0.0038 meter^3
1 ft^3 = 0.028 meter^3

Mass: 1 lb = 0.45 kilogram

Pressure: 1 in. Hg = 0.033 atmosphere
1 psi = 0.068 atmosphere

Velocity: 1 mph = 0.45 meter/second

Energy: 1 Btu = 252 calories
1 kWh = 860 kilocalories

Power: 1 hp = 0.75 kilowatt

Temperature: change of 1° F = 0.556° C
to convert $^{\circ}C = \frac{5(^{\circ}F - 32)}{9}$